Wave Forces on Windturbine Foundations

for the London Array

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Publication date:
2005

Document Version
Early version, also known as pre-print

Link to publication from Aalborg University

Citation for published version (APA):
Larsen, B. J., & Frigaard, P. (2005). *Wave Forces on Windturbine Foundations: for the London Array*. Department of Civil Engineering, Aalborg University. Hydraulics and Coastal Engineering No. 30

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Wave Forces on Windturbine Foundations

for the London Array

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Hydraulics and Coastal Engineering No. 30

ISSN 1603-9874

August 2005

Wave Forces on Windturbine Foundations

for the London Array

by

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Contents

Introduction

By request from CORE Ltd. / Energi E2 A/S a test programme has been performed to determine the wave forces on two types of foundation for an offshore windturbine. The tested foundation types are a monopile and cone. Furthermore the shaft of the cone has been tested.

For further information on the conducted test programme contact Brian Juul Larsen (phone: 96 35 72 31, email: i5bjl@civil.aau.dk) or Peter Frigaard (phone: 96 35 84 79, email: peter.frigaard@civil.aau.dk).

Tests

Scaling

The tests are performed with a length scale of 1:50. All values are scaled according to Froudes modellaw:

Length: $\lambda_L = 50$
Time: $\lambda_T = \lambda_L^{1/2} = 7.07$

All measures in the following report will be in prototype values if nothing else is mentioned.

Description of Models

The two types of foundation that are being tested are shown underneath in figure 1. In appendix 2 the models are shown in detail.

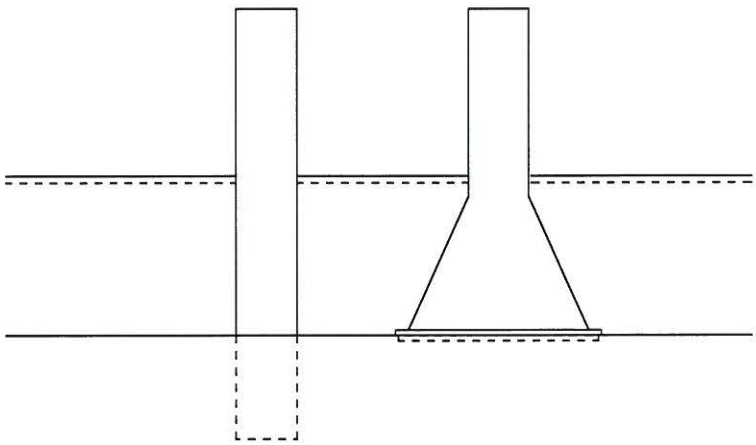


Figure 1. Monopile and concrete cone.

The models are made of various types of plastic.

Description of Set-up

The tests are conducted in a wave flume that is 945 meters long and 75 meters wide, see figure 2.

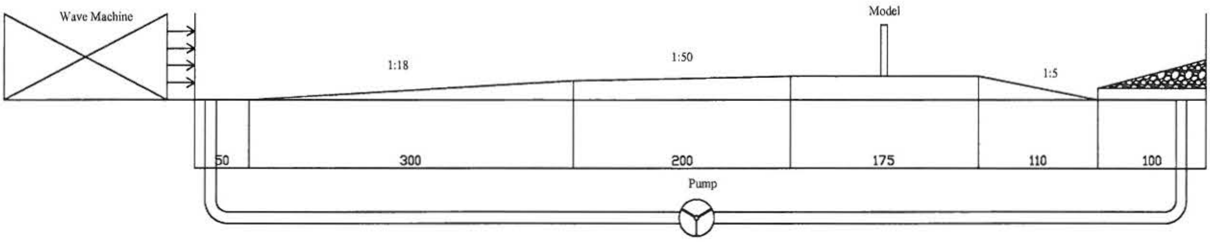


Figure 2. The wave flume. All measures in meters.

Waves

All tests were made with a JONSWAP spectra. The peak enhancement factor, γ, is at all times set at 3.3. The duration of the tests was 3½ h or 1300 to 2200 waves depending on period.

Measurements

The wave elevation signal was measured beside the model by means of three wave gauges to separate the incoming and reflected waves by means of the method by Mansard and Funke (1986). The current velocity has been measured with an ultrasonic flowmeter. The forces on the monopile are measured with a strain gauge based force cell that measures force and moment in three directions perpendicular to each other. The forces on the concrete cone are measured as two moments in two different heights above the model. As it can be seen from the figures in appendix 1 the wave gauges are mounted slightly in front of the model. (Approximately the quarter of a wave length. The waves peak more or less together with the forces in stead of T/4 after).

Test programme

Test No.	H_s [m]	H_{m0} [m]	T_p [m]	h [m]	U [m/s]	Waves	Structure
F01	2.07	2.17	6.5	9	0	2142	Monopile
F02	3.76	3.98	9.1	9	0	1583	Monopile
F03	4.91	5.30	11.7	9	0	1329	Monopile
F04	2.02	2.21	6.5	12	0	2127	Monopile
F05	3.63	3.95	9.3	12	0	1594	Monopile
F06	5.65	6.01	11.3	12	0	1312	Monopile
F07	1.89	2.02	6.6	15	0	2104	Monopile
F08	3.47	3.75	9.3	15	0	1586	Monopile
F09	5.34	5.67	11.3	15	0	1278	Monopile
F10	2.19	2.41	6.6	9	1.5	2016	Monopile
F11	5.06	5.55	11.7	15	1.5	1267	Monopile
F12	2.31	2.52	6.5	9	0	2213	Concrete cone
F13	4.79	5.06	9.1	9	0	1555	Concrete cone
F14	6.48	6.84	11.7	9	0	1314	Concrete cone
F15	2.47	2.71	6.5	12	0	2179	Concrete cone
F16	4.85	5.17	9.1	12	0	1591	Concrete cone
F17	7.76	8.15	11.7	12	0	1256	Concrete cone
F18	2.47	2.74	6.5	15	0	2182	Concrete cone
F19	4.71	4.86	9.3	15	0	1558	Concrete cone
F20	7.61	8.04	11.3	15	0	1254	Concrete cone
F21	3.16	3.51	6.5	9	1.5	2088	Concrete cone
F22	7.84	8.19	11.3	15	1.5	1268	Concrete cone
F23	2.51	2.69	6.5	9	0	2144	Shaft of cone
F24	7.39	7.85	11.3	15	0	1271	Shaft of cone

Table 1. Test programme.

On the inside of the backside there is CD attached with a 1 minute movie clip from each test. There is also a exe file with the required video codec. The CD also contains the raw uninterpreted output files from the 24 tests.

Results

Test No.	H_{m0} [m]	$F_{h,max}$ [kN]	$F_{h,min}$ [kN]	M_{max} [kNm]	M_{min} [kNm]
F01	2.17	879	-1002	8360	-7340
F02	3.98	1534	-1293	9087	-7872
F03	5.30	2622	-1374	16456	-9456
F04	2.21	1033	-1116	10622	-8638
F05	3.95	1271	-1327	10700	-10724
F06	6.01	3995	-1910	75678	-12388
F07	2.02	1072	-1200	12056	-11390
F08	3.75	1681	-1568	17151	-13764
F09	5.67	5120	-2197	77112	-17942
F10	2.41	1149	-867	7904	-20094
F11	5.55	5370	-2183	85325	-23539
F12	2.52	3339	-4497	39181	-37261
F13	5.06	5381	-5251	68899	-77336
F14	6.84	7867	-5986	105442	-85717
F15	2.71	3615	-3781	41461	-40230
F16	5.17	5031	-4476	60476	-43665
F17	8.15	8402	-5833	116356	-74609
F18	2.74	3129	-2373	41116	-32662
F19	4.86	4963	-4337	61444	-50593
F20	8.04	9065	-6098	133309	-68145
F21	3.51	4991	-4442	62153	-59566
F22	8.19	9894	-6166	139241	-73882
F23	2.69	384	-428	12900	-14340
F24	7.85	5074	-3152	121939	-85220

Table 2. Test results.

Test No.	H_{m0} [m]	$F_{h,1/250,max}$ [kN]	$F_{h,1/250,min}$ [kN]	$M_{1/250,max}$ [kNm]	$M_{1/250,min}$ [kNm]
F01	2.17	717	-712	5947	-5611
F02	3.98	1014	-981	5430	-5240
F03	5.30	1228	-1042	5985	-4116
F04	2.21	870	-900	6056	-6337
F05	3.95	1112	-1152	7165	-7170
F06	6.01	1737	-1410	12950	-8830
F07	2.02	945	-876	8345	-7769
F08	3.75	1327	-1319	10700	-9820
F09	5.67	2194	-1770	19540	-14210
F10	2.41	763	-734	4159	-4830
F11	5.55	2020	-1643	19470	-12580
F12	2.52	2938	-2852	26560	-25270
F13	5.06	4244	-3575	36090	-24440
F14	6.84	4826	-3995	40090	-32120
F15	2.71	2814	-2530	26960	-24130
F16	5.17	4258	-3731	37940	-28210
F17	8.15	5774	-4361	52690	-34530
F18	2.74	2288	-2057	24040	-20090
F19	4.86	4076	-3564	37890	-27960
F20	8.04	6025	-4982	59490	-41490
F21	3.51	3704	-3140	35080	-30370
F22	8.19	5892	-4770	60930	-40550
F23	2.69	48	-47	1590	-1595
F24	7.85	1520	-980	35220	-24330

Table 3. 1/250 values.

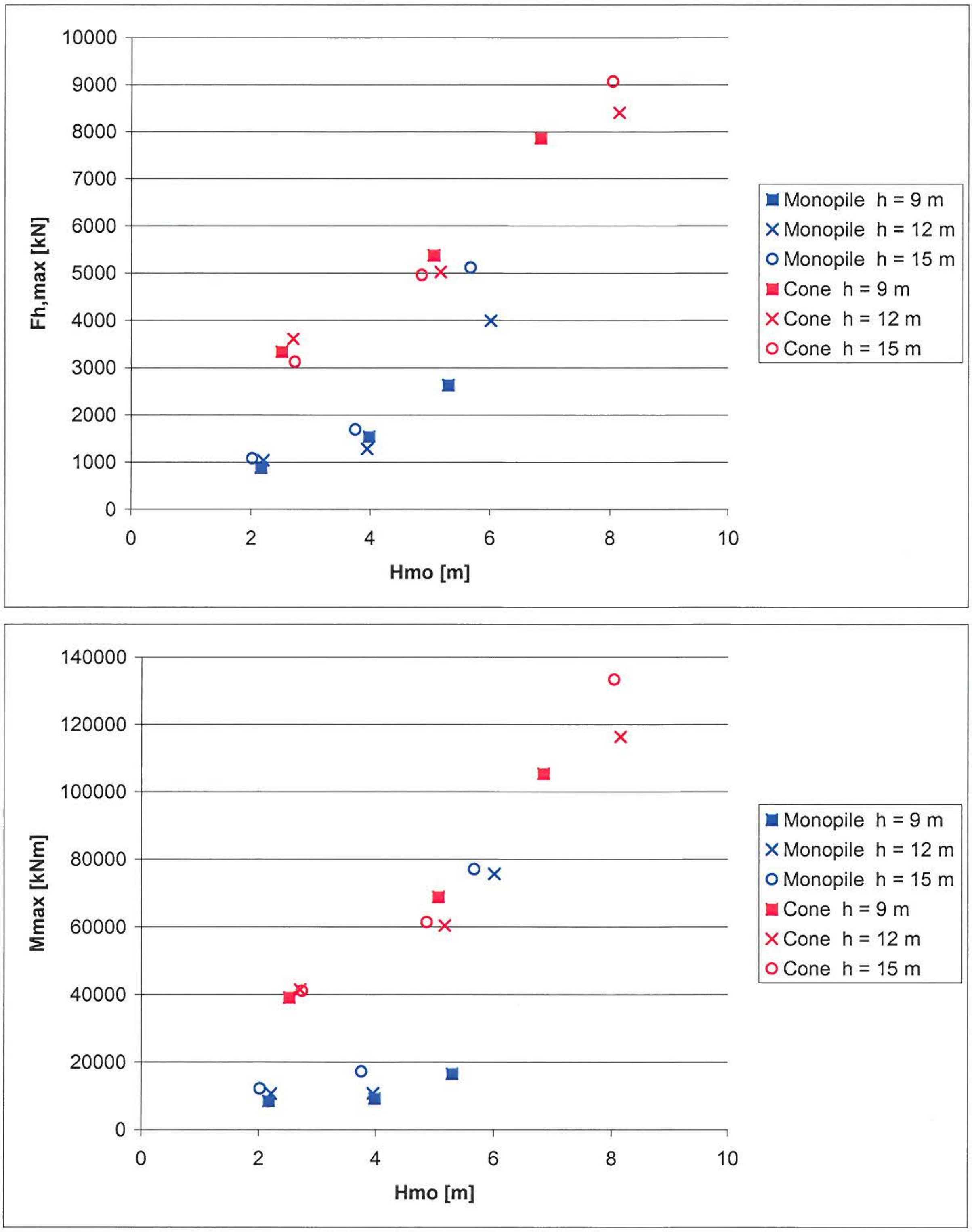
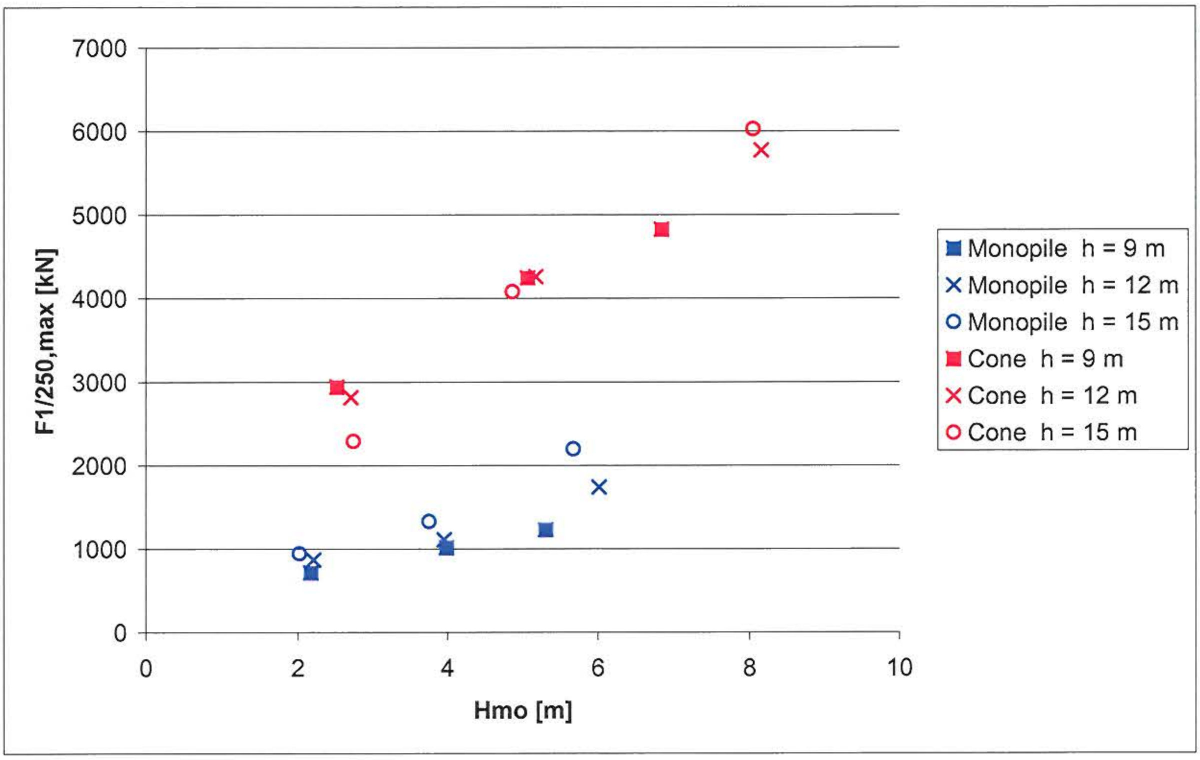


Figure 3. $F_{h,max}$ and M_{max} as a function of H_{m0}.



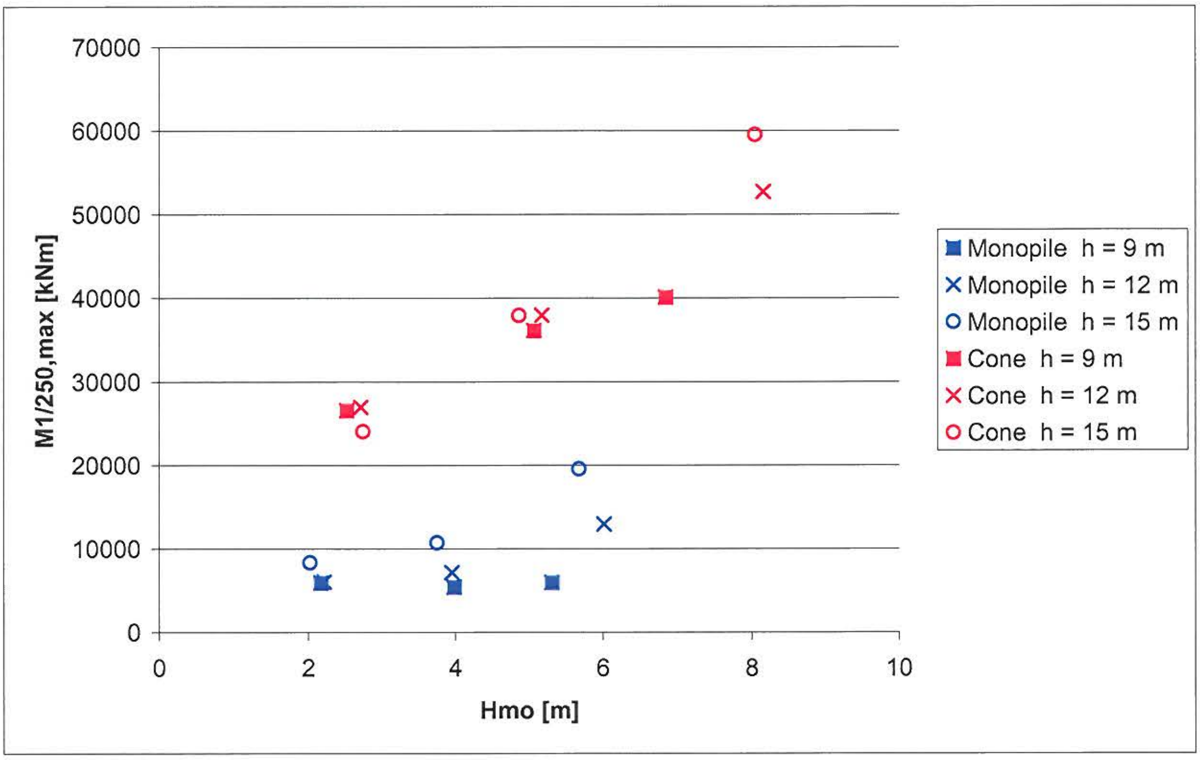
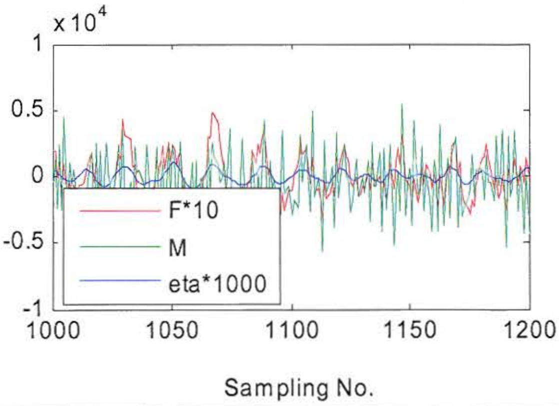


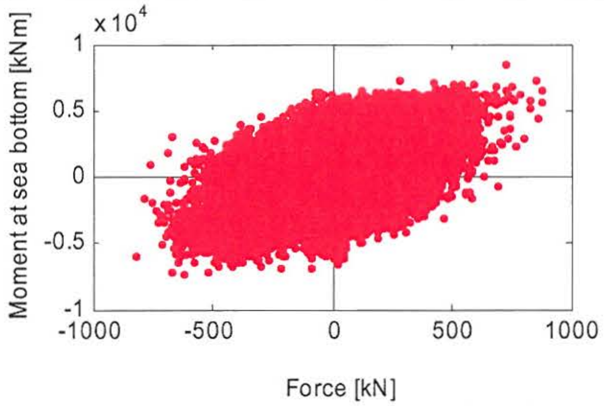
Figure 4. $F_{h,1/250,max}$ and $M_{1/250,max}$ as a function of H_{m0}.

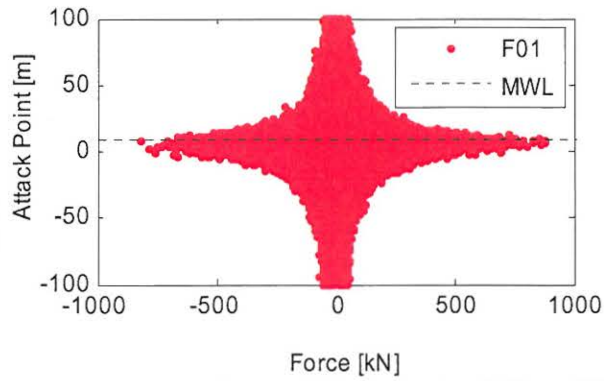
Appendix 1 – Results

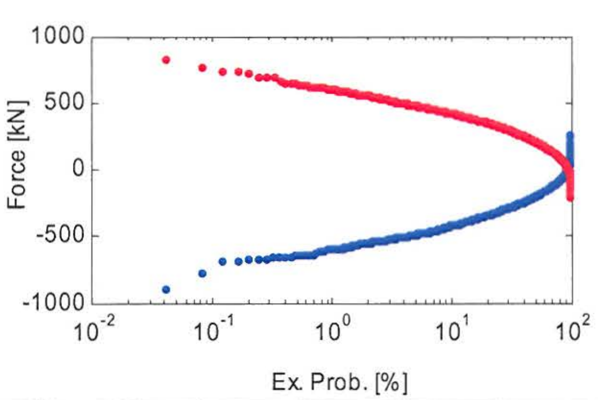
F01

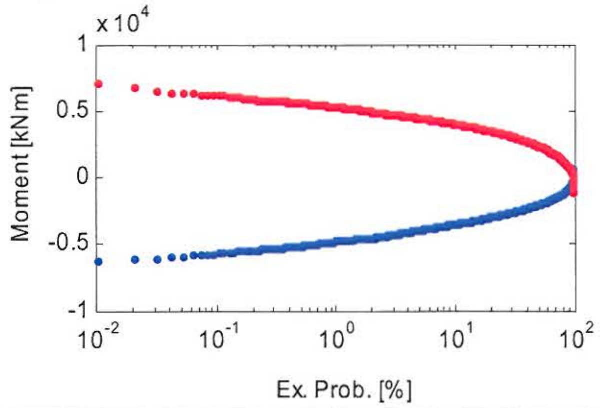
- With a monopile
- H_{m0} = 2.17 m, Tp = 6.5 s, h = 9 m
- $F_{h,max}$ = 879 kN
- $F_{h,min}$ = -1002 kN
- M_{max} = 8360 kNm
- M_{min} = -7340 kNm

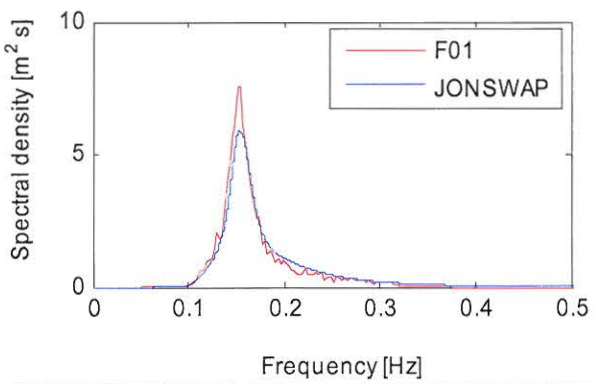


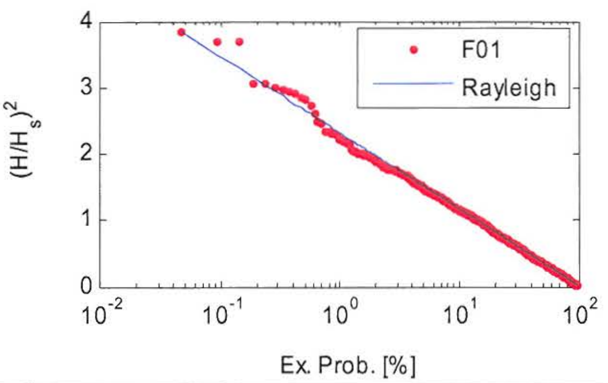






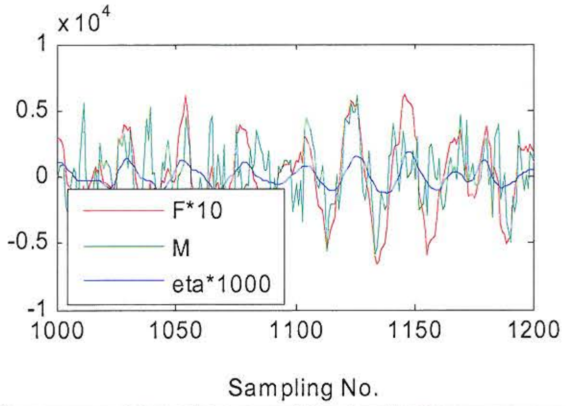


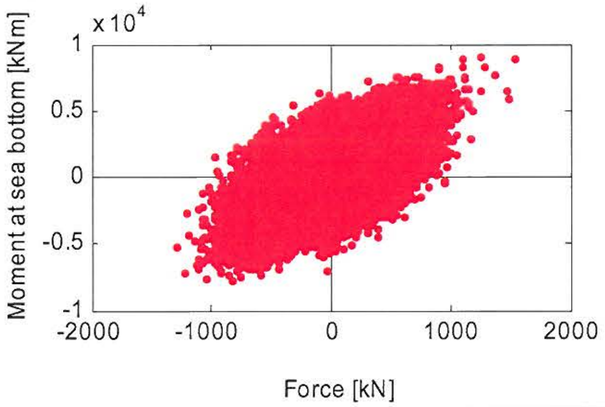


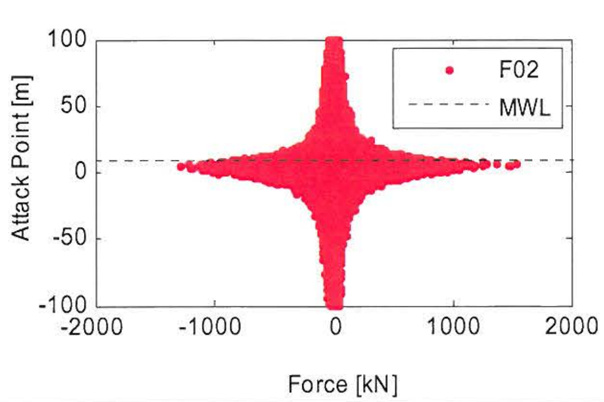


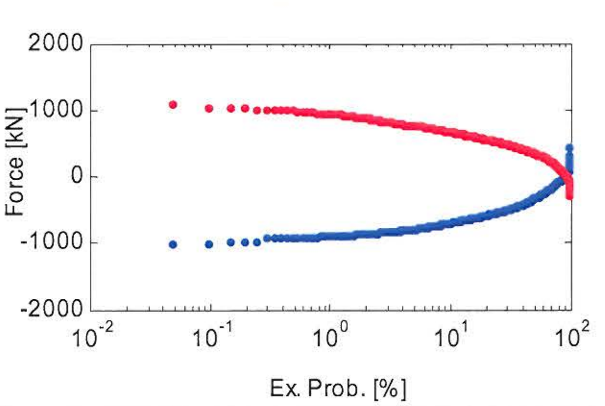
F02

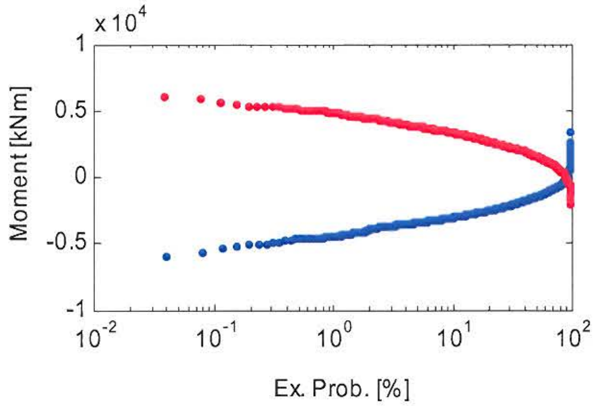
- With a monopile
- H_{m0} = 3.98 m, Tp = 9.1 s, h = 9 m
- $F_{h,max}$ = 1534 kN
- $F_{h,min}$ = -1293 kN
- M_{max} = 9087 kNm
- M_{min} = -7872 kNm

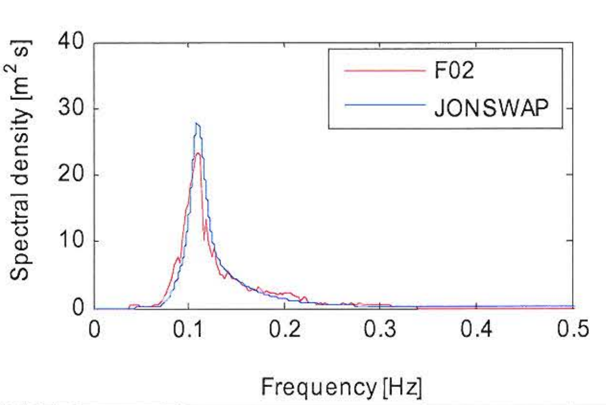


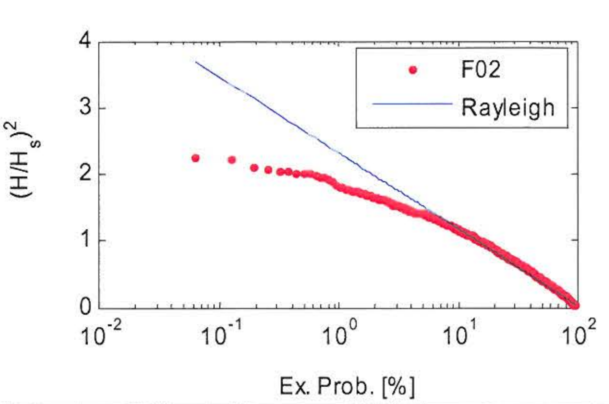






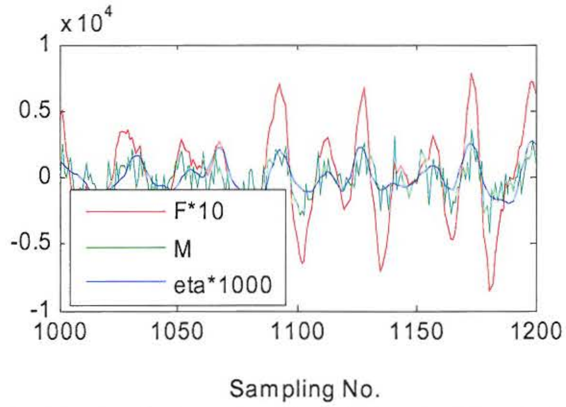


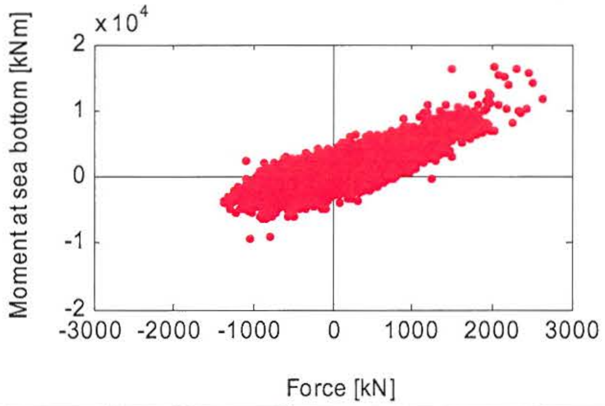


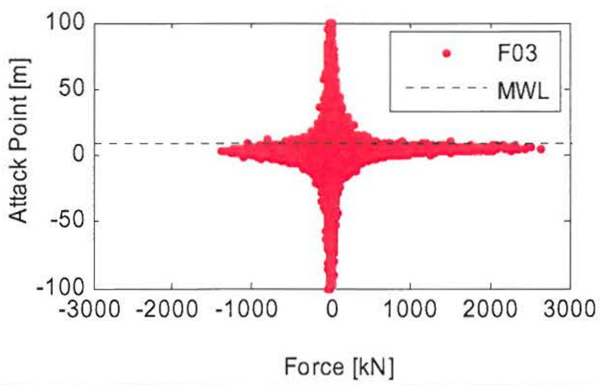


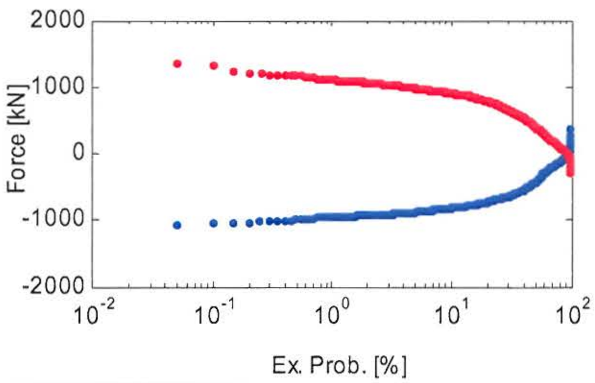
F03

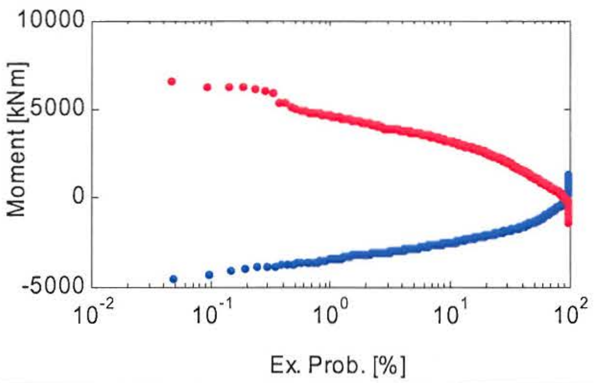
- With a monopile
- H_{m0} = 5.30 m, Tp = 11.7 s, h = 9 m
- $F_{h,max}$ = 2622 kN
- $F_{h,min}$ = -1374 kN
- M_{max} = 16456 kNm
- M_{min} = -9456 kNm

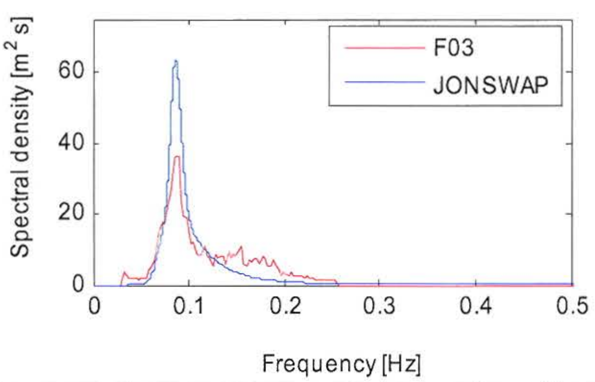


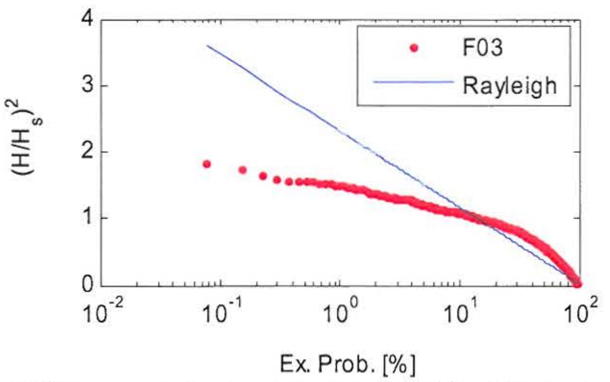






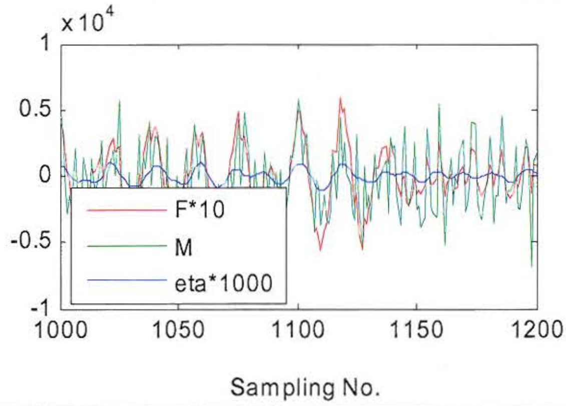


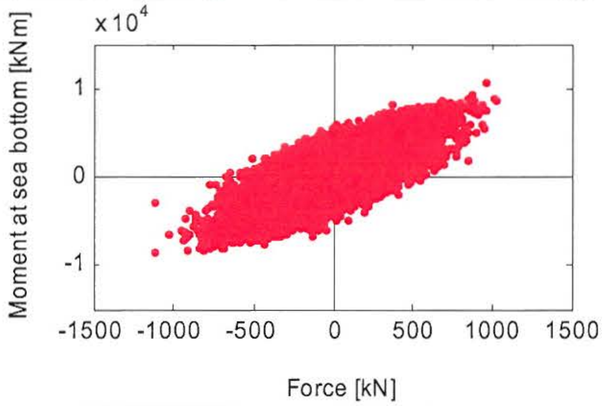


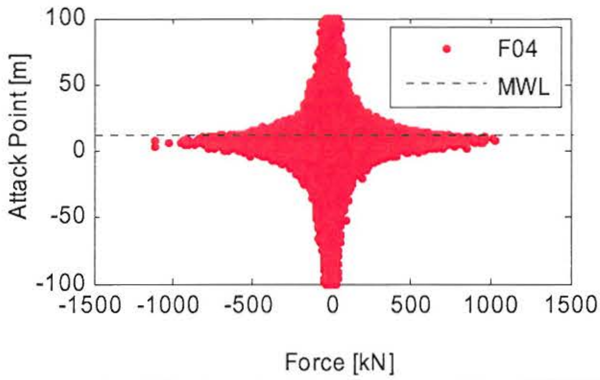


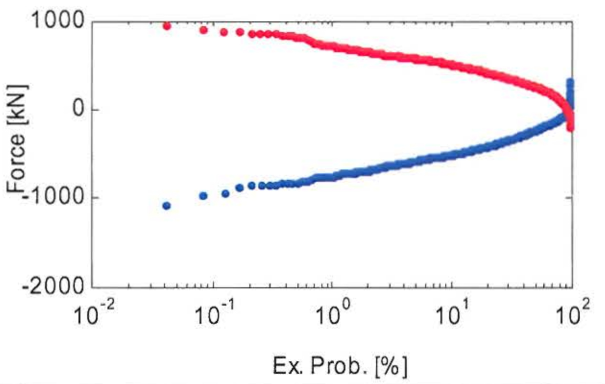
F04

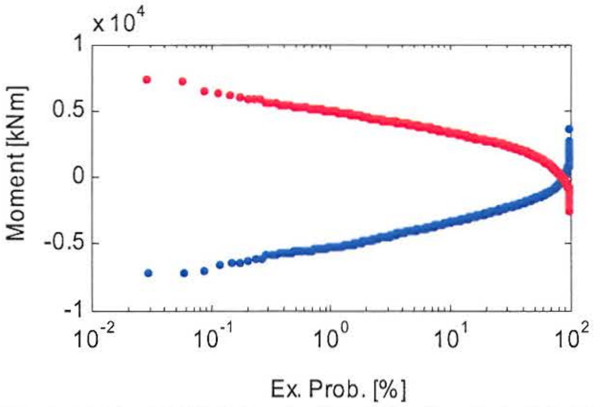
- With a monopile
- $H_{m0} = 2.21$ m, $Tp = 6.5$ s, $h = 12$ m
- $F_{h,max} = 1033$ kN
- $F_{h,min} = -1116$ kN
- $M_{max} = 10622$ kNm
- $M_{min} = -8638$ kNm

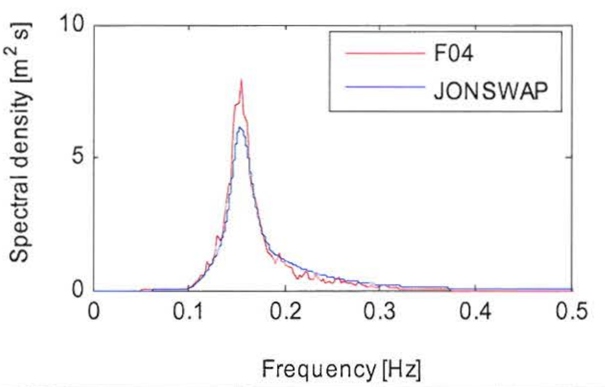


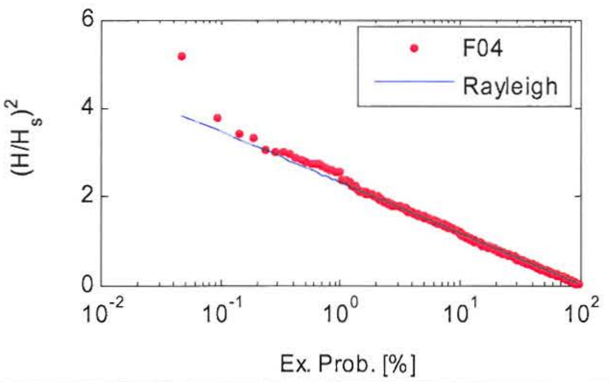






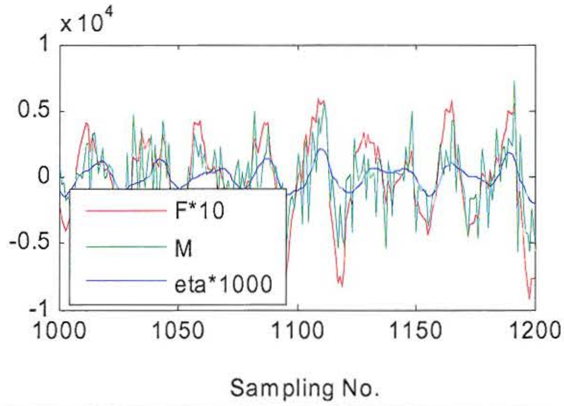


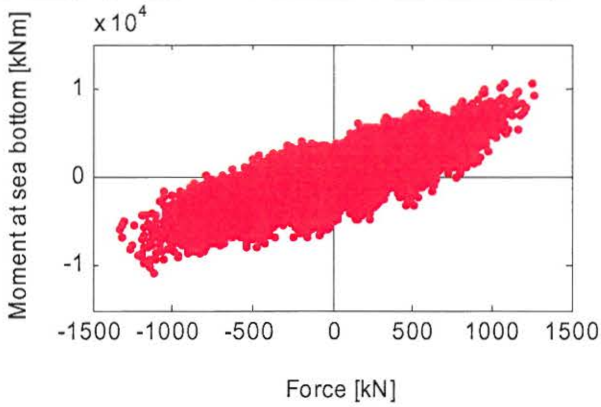


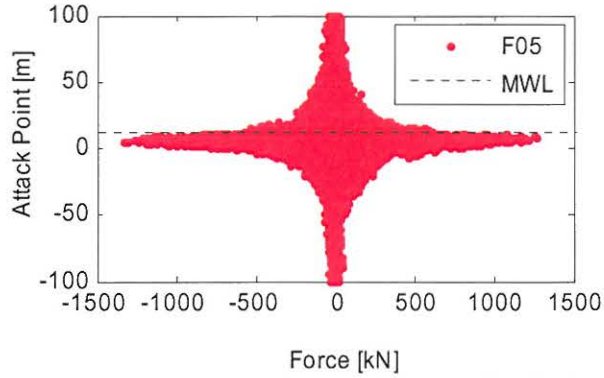


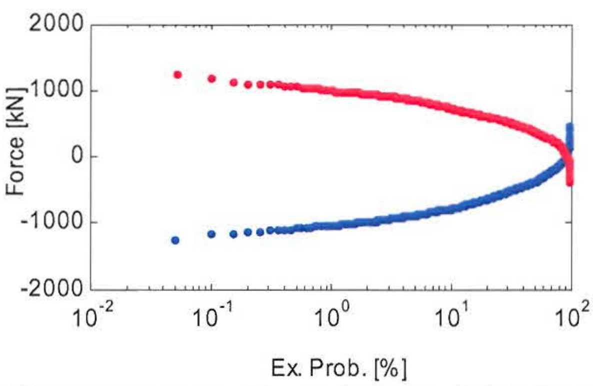
F05

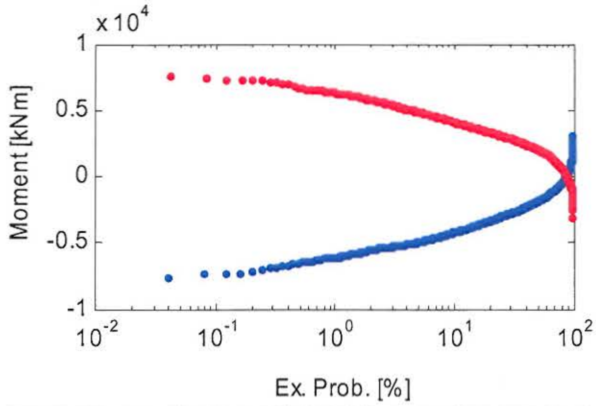
- With a monopile
- H_{m0} = 3.95 m, Tp = 9.3 s, h = 12 m
- $F_{h,max}$ = 1271 kN
- $F_{h,min}$ = -1327 kN
- M_{max} = 10700 kNm
- M_{min} = -10724 kNm

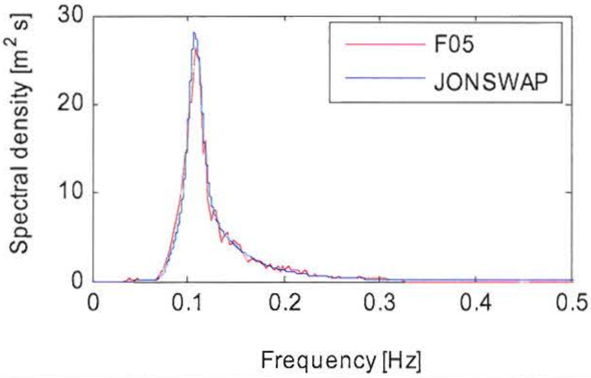


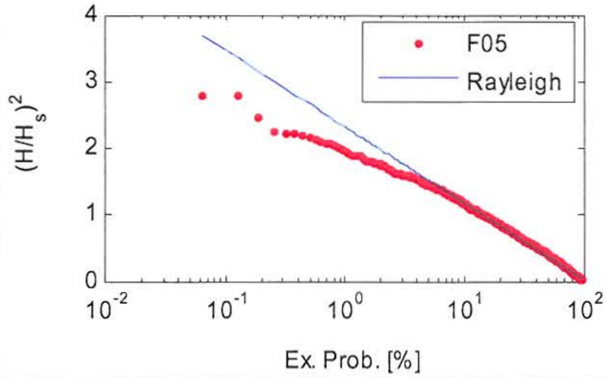






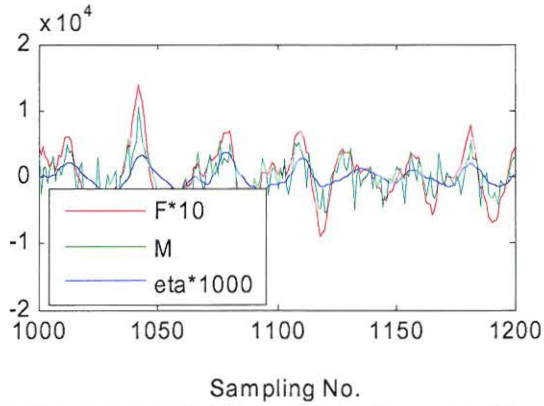


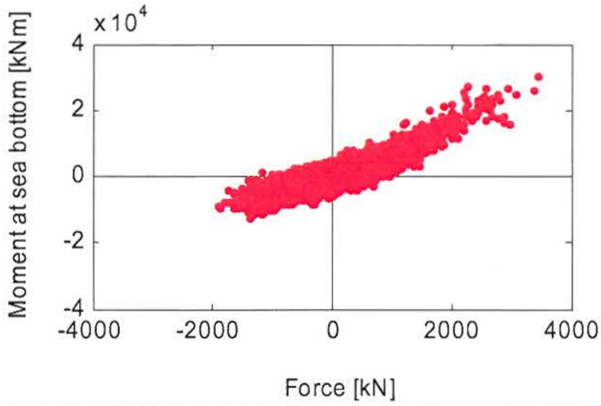


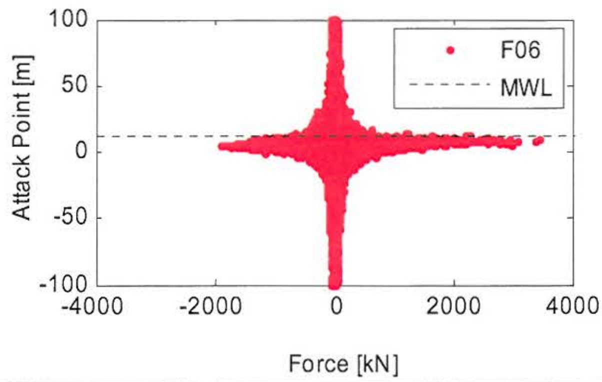


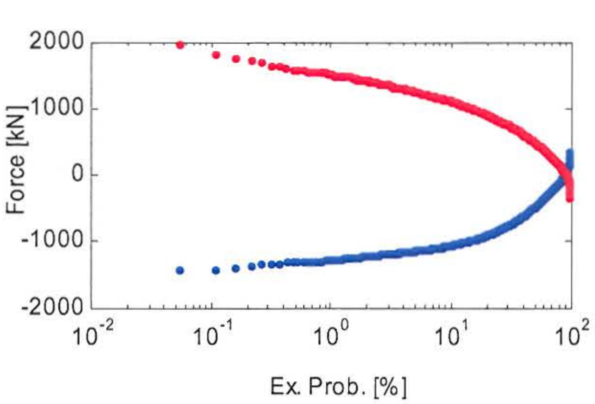
F06

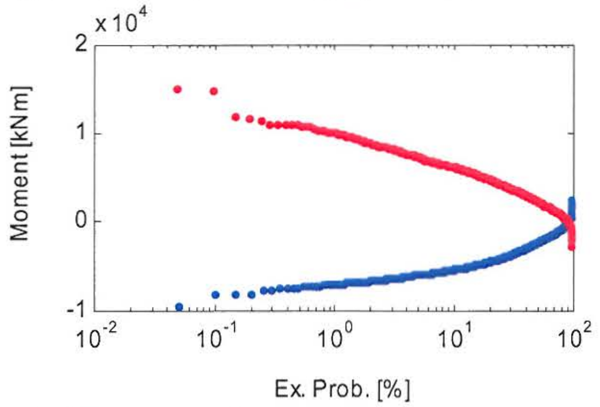
- With a monopile
- H_{m0} = 6.01 m, Tp = 11.3 s, h = 12 m
- $F_{h,max}$ = 3433 kN
- $F_{h,min}$ = -1910 kN
- M_{max} = 30336 kNm
- M_{min} = -12388 kNm

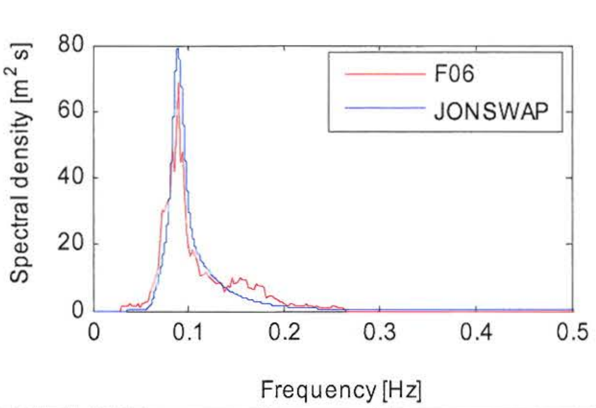


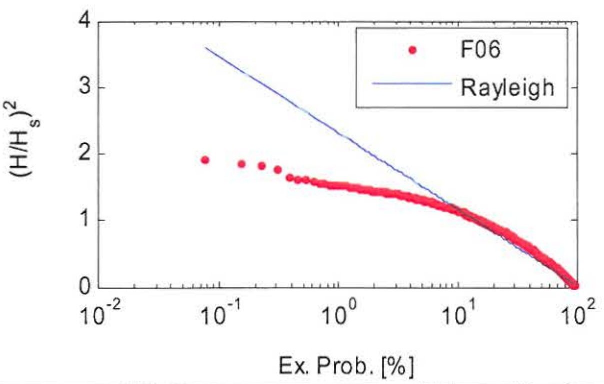






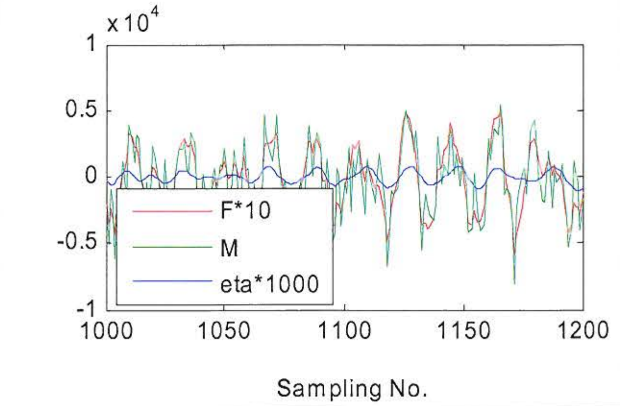


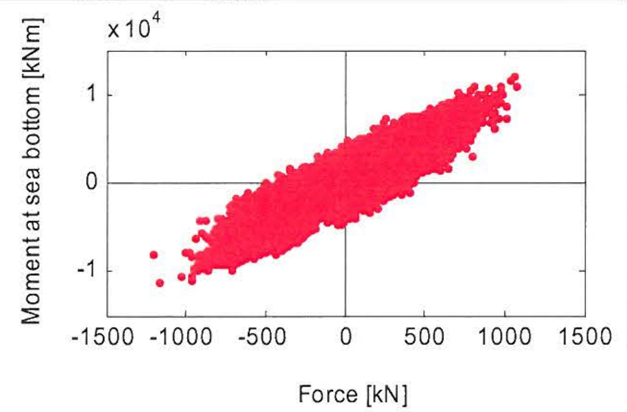


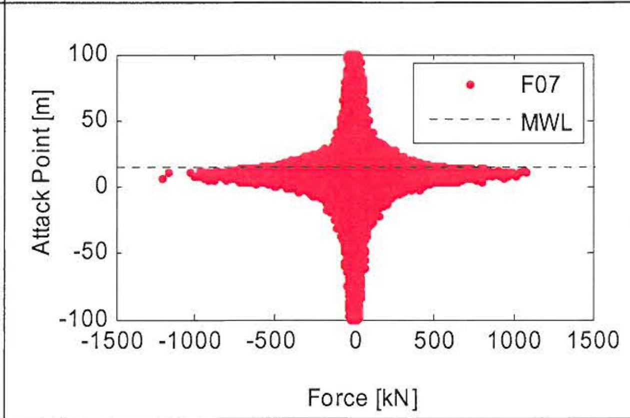


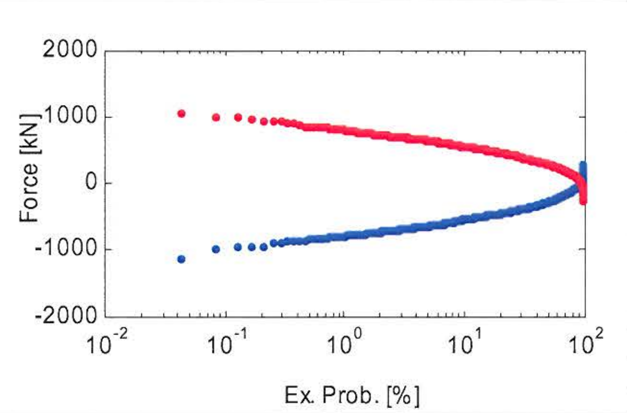
F07

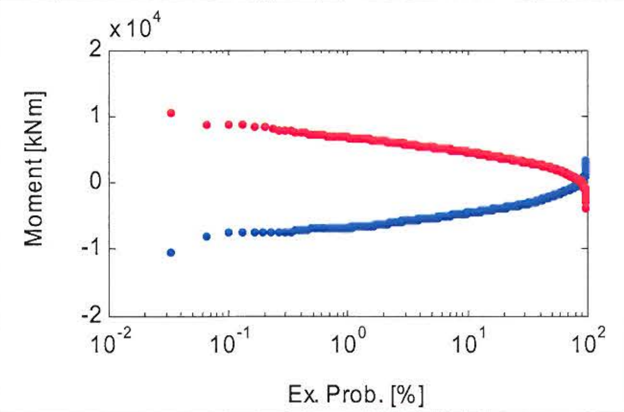
- With a monopile
- $H_{m0} = 2.02$ m, $Tp = 6.6$ s, $h = 15$ m
- $F_{h,max} = 1072$ kN
- $F_{h,min} = -1200$ kN
- $M_{max} = 12056$ kNm
- $M_{min} = -11390$ kNm

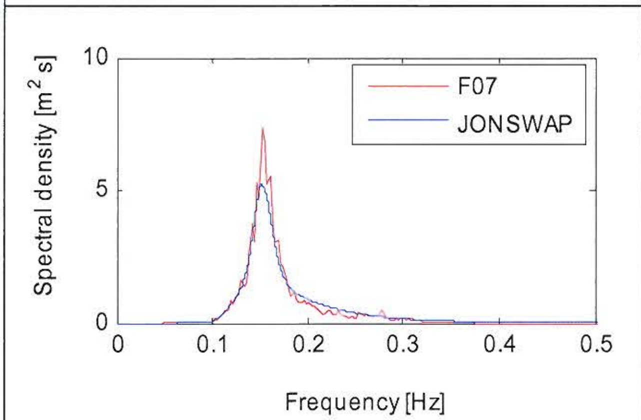


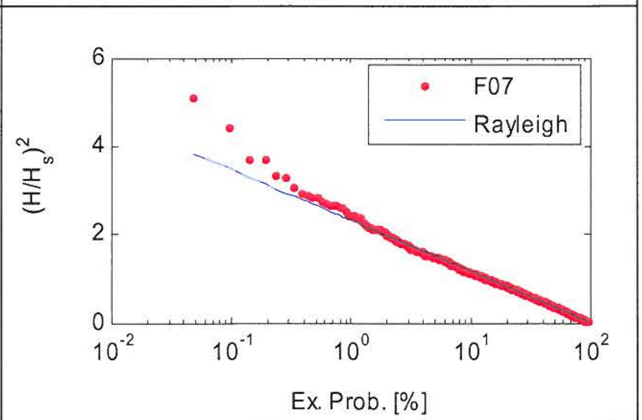






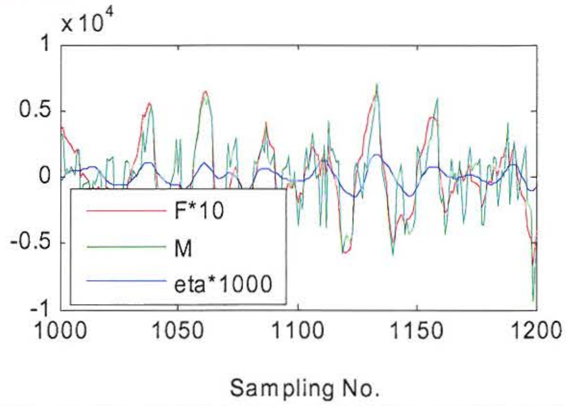


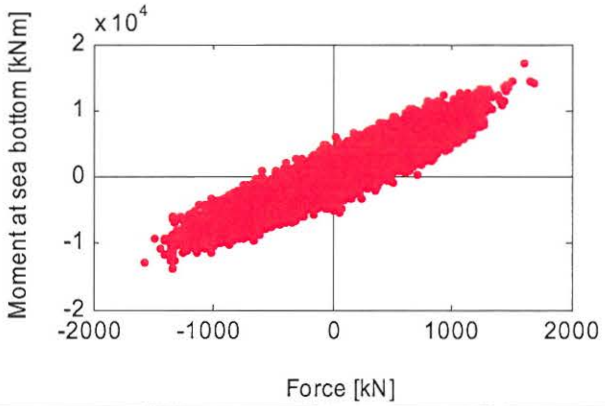


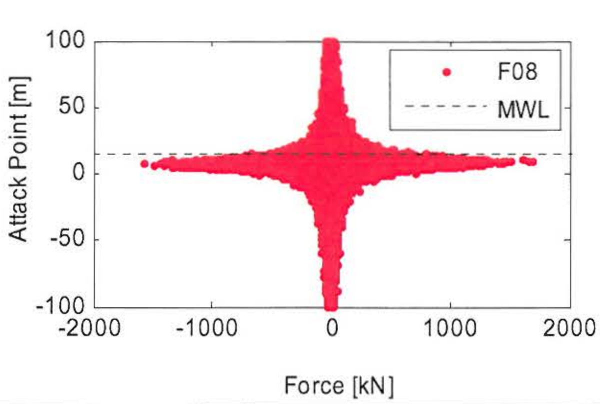


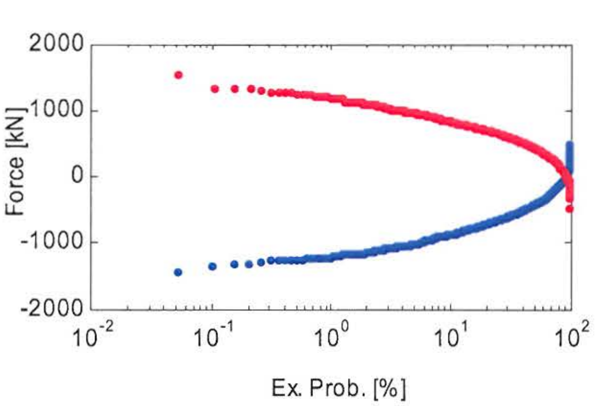
F08

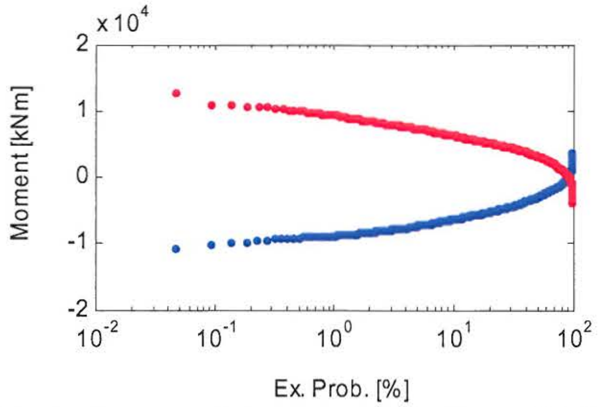
- With a monopile
- H_{m0} = 3.75 m, Tp = 9.3 s, h = 15 m
- $F_{h,max}$ = 1681 kN
- $F_{h,min}$ = -1568 kN
- M_{max} = 17151 kNm
- M_{min} = -13764 kNm

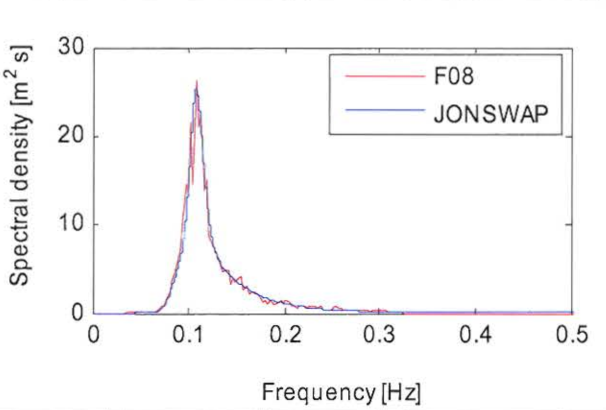


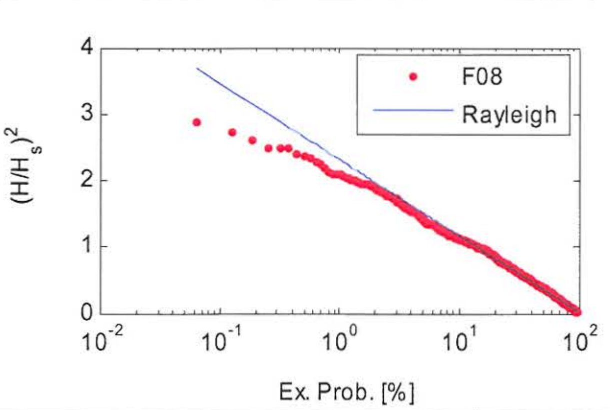






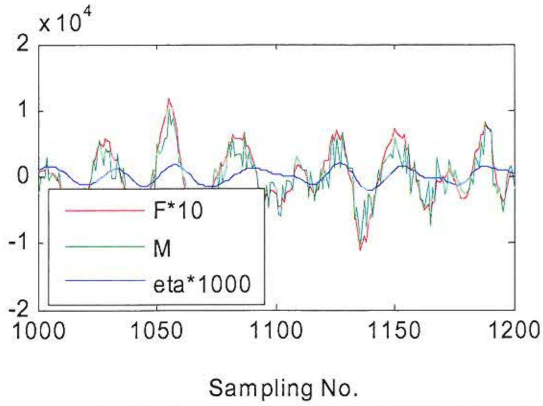


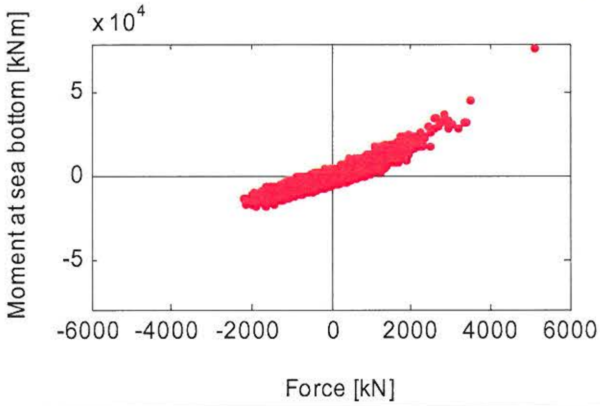


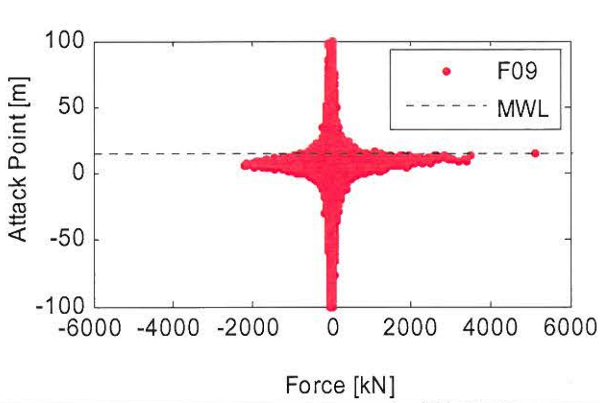


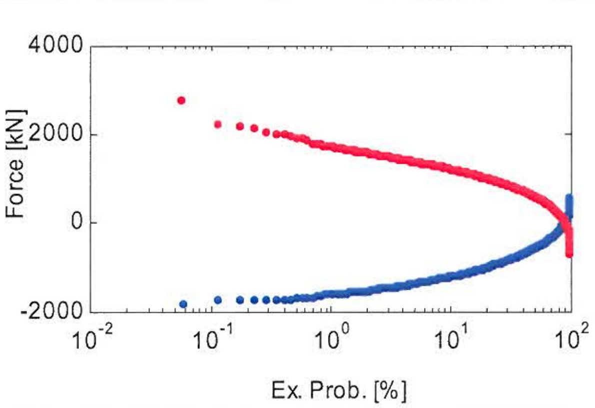
F09

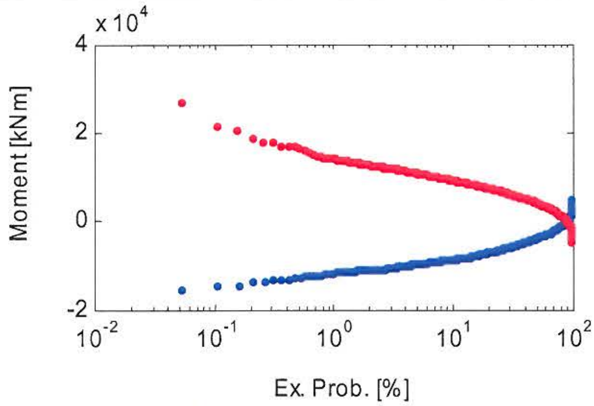
- With a monopile
- H_{m0} = 5.67 m, Tp = 11.3 s, h = 15 m
- $F_{h,max}$ = 5120 kN
- $F_{h,min}$ = -2197 kN
- M_{max} = 77112 kNm
- M_{min} = -17942 kNm

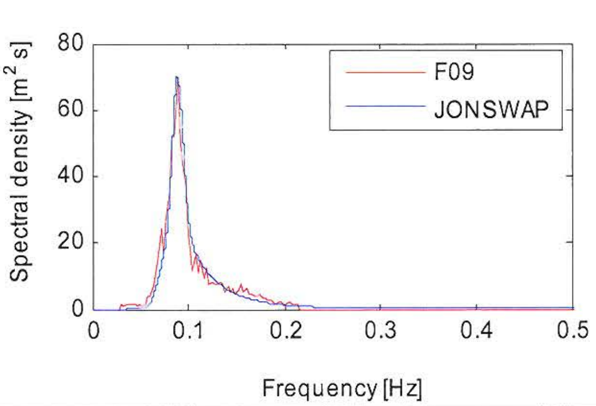


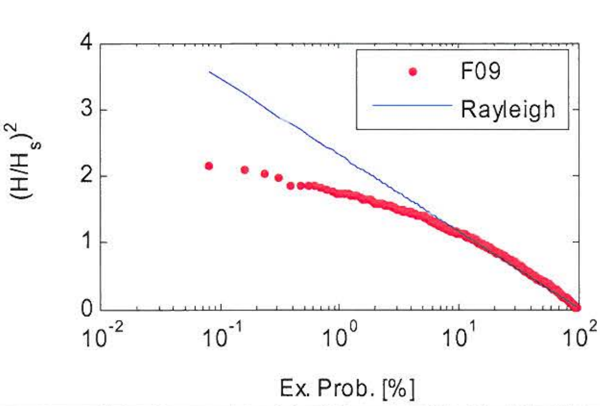






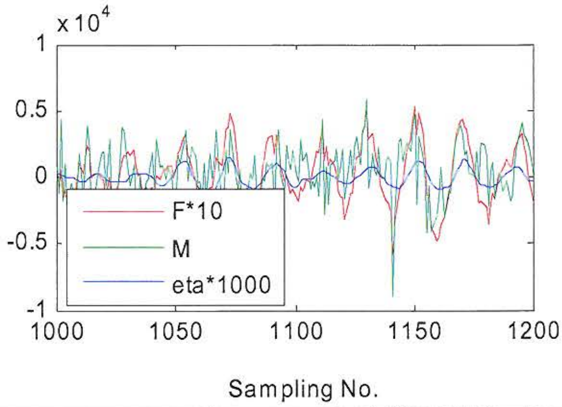


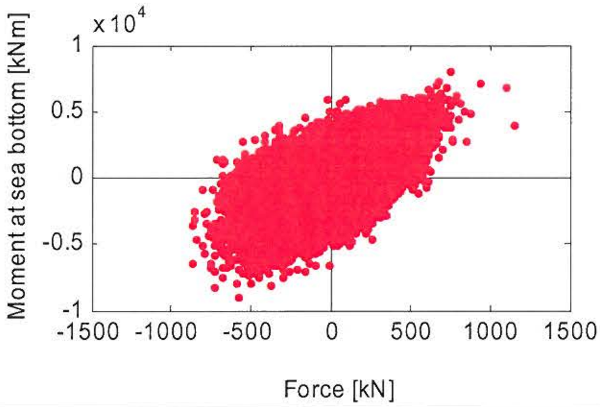


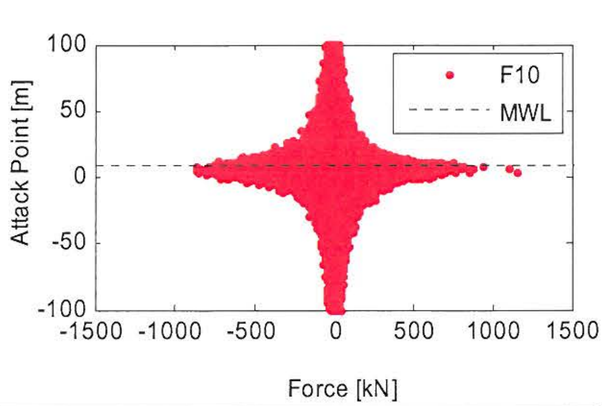


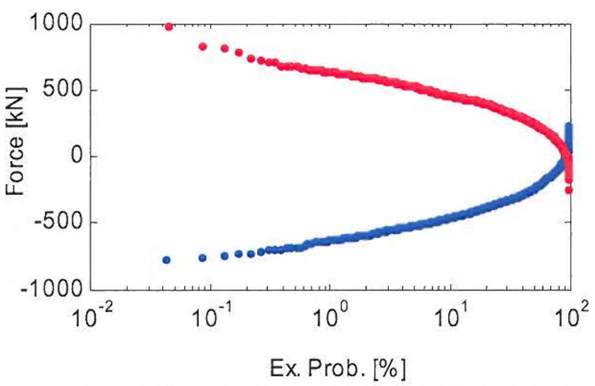
F10

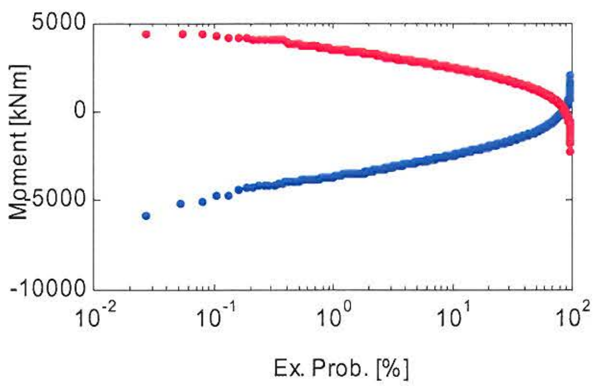
- With a monopile
- H_{m0} = 2.41 m, Tp = 6.6 s, h = 9 m, U = 1.5 m/s
- $F_{h,max}$ = 1149 kN
- $F_{h,min}$ = -867 kN
- M_{max} = 7904 kNm
- M_{min} = -9011 kNm

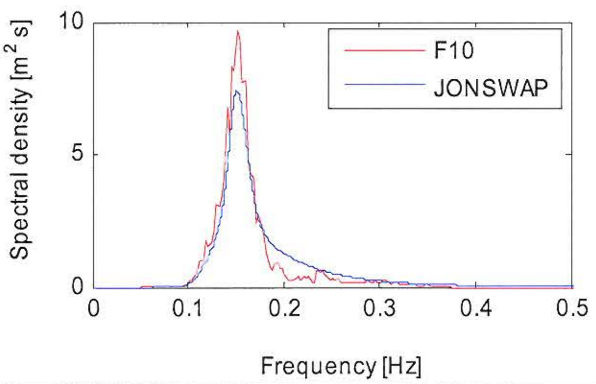


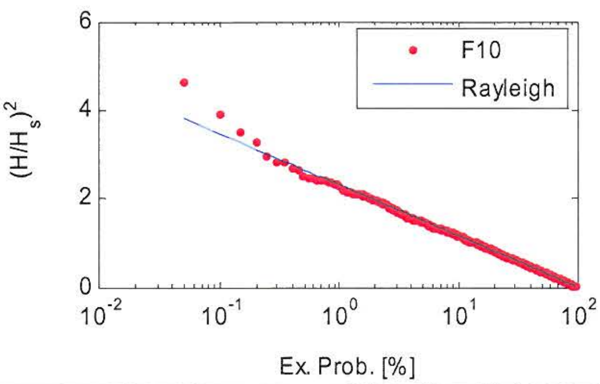






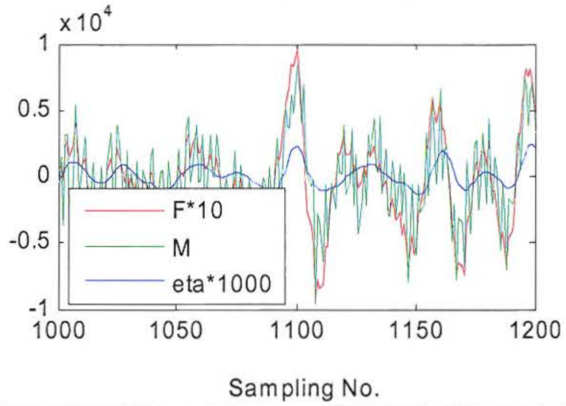


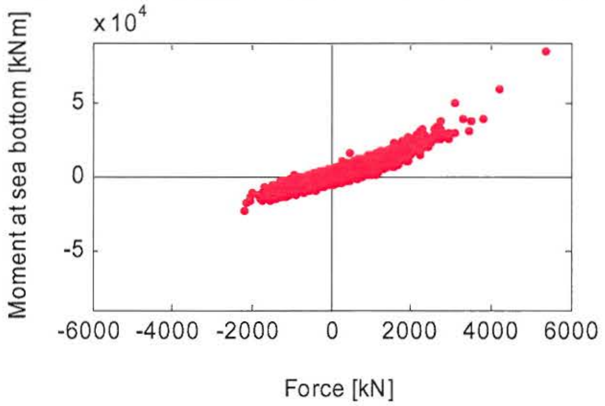


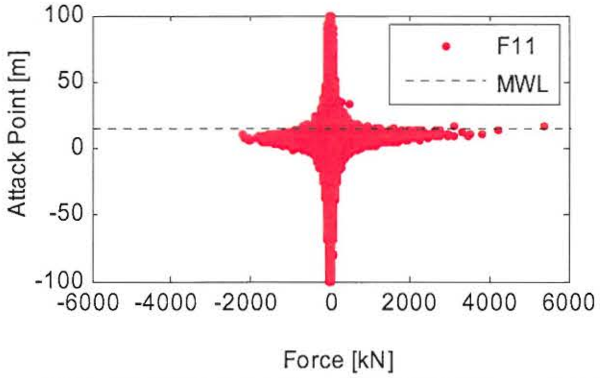


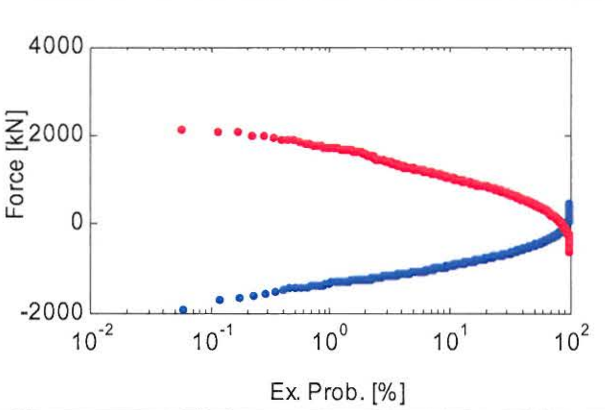
F11

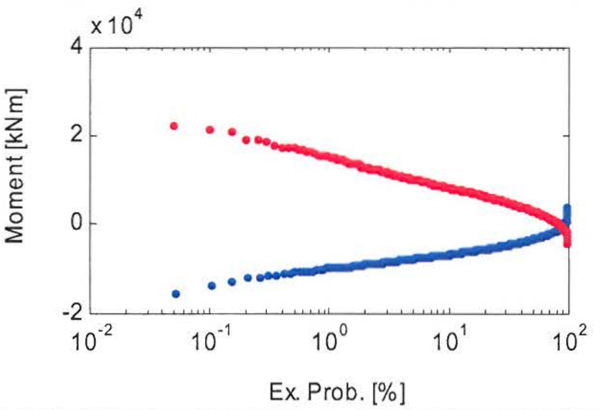
- With a monopile
- H_{m0} = 5.55 m, Tp = 11.7 s, h = 15 m, U = 1.5 m/s
- $F_{h,max}$ = 5370 kN
- $F_{h,min}$ = -2183 kN
- M_{max} = 85325 kNm
- M_{min} = -23539 kNm

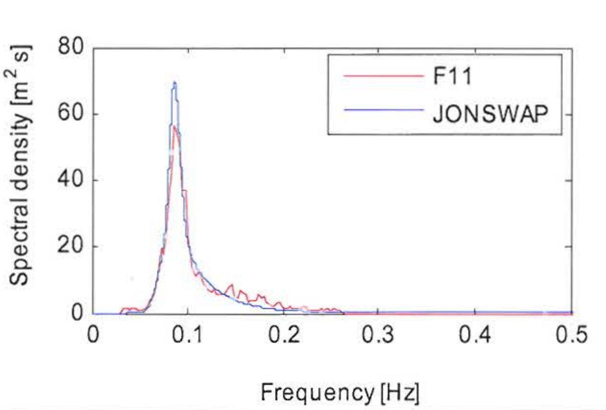


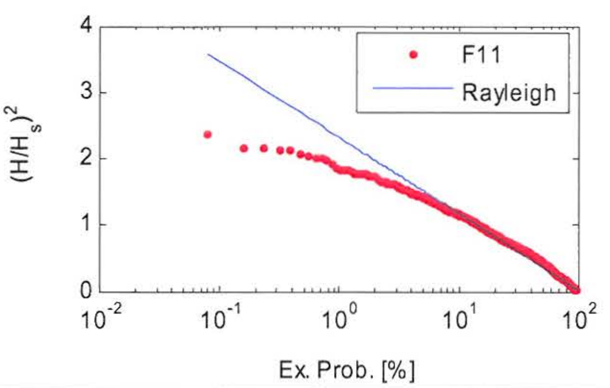






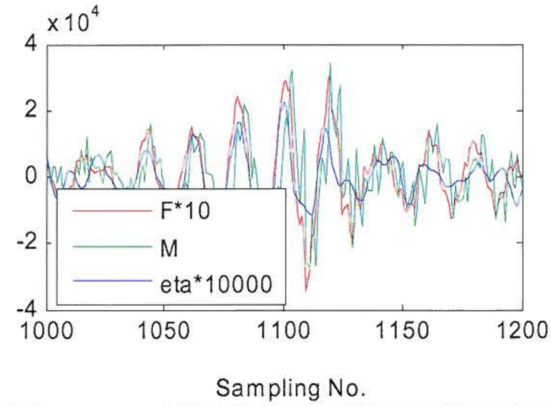


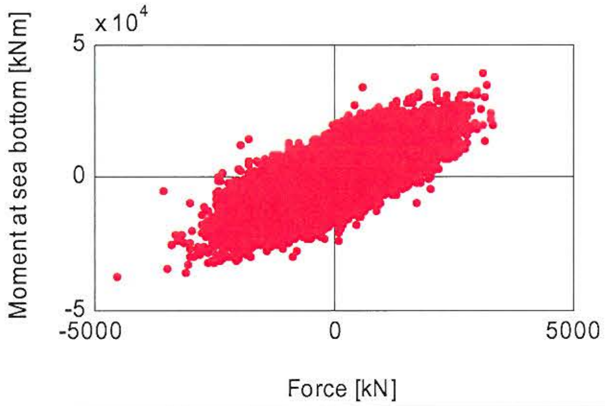


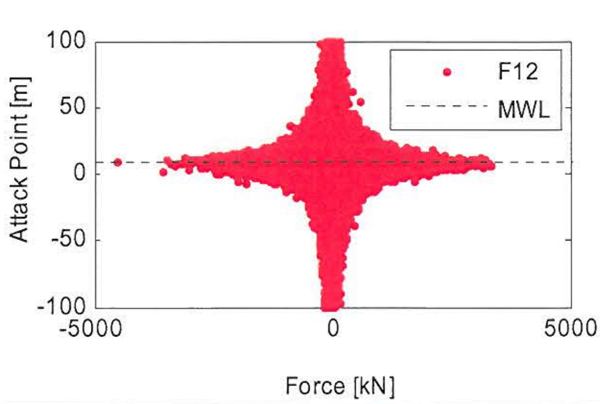


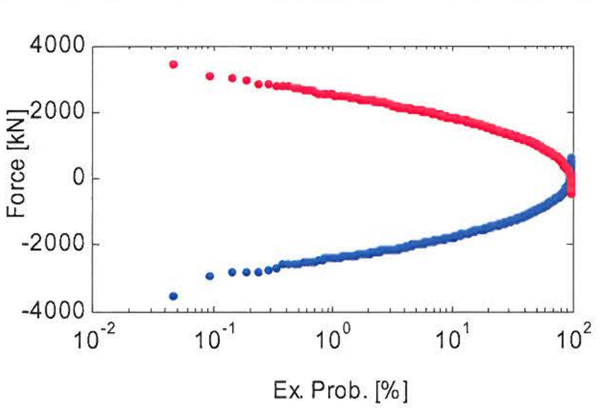
F12

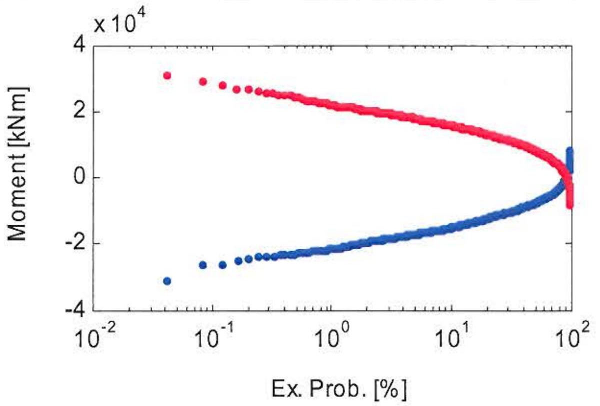
- With a concrete cone
- H_{m0} = 2.52 m, Tp = 6.5 s, h = 9 m
- $F_{h,max}$ = 3339 kN
- $F_{h,min}$ = -4497 kN
- M_{max} = 39181 kNm
- M_{min} = -37261 kNm

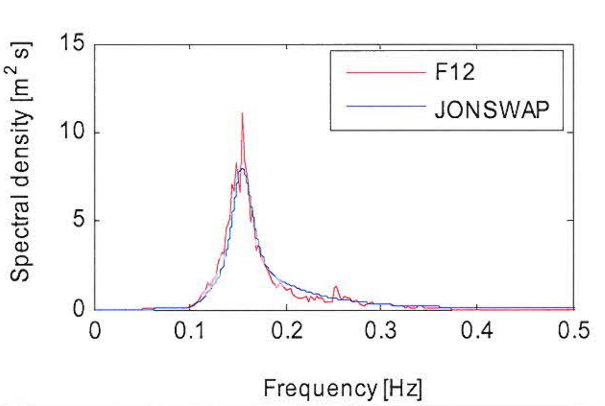


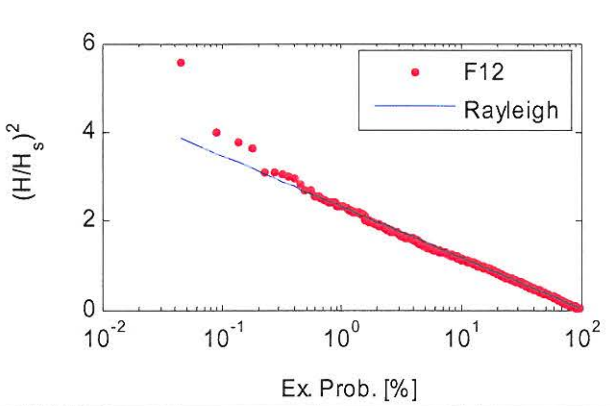






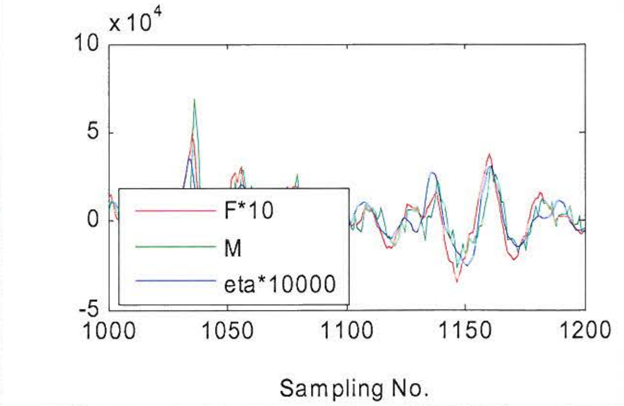


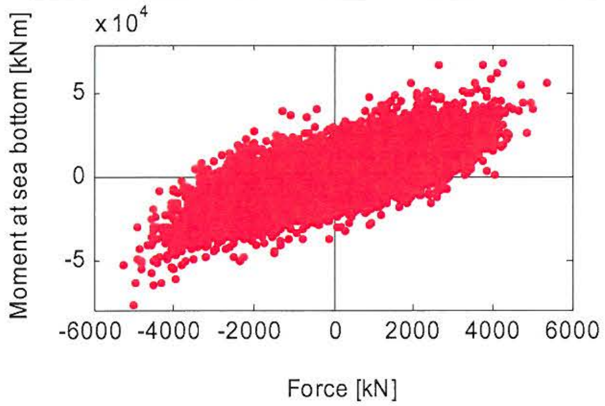


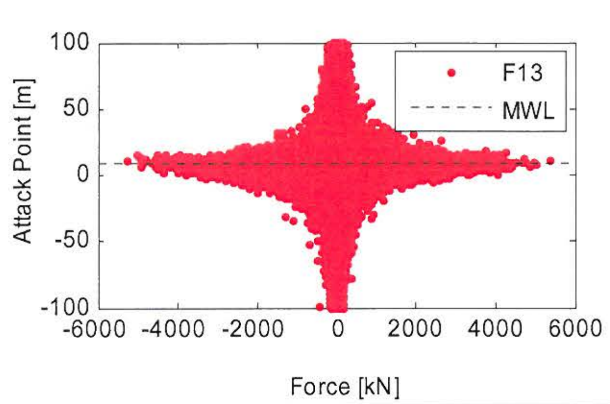


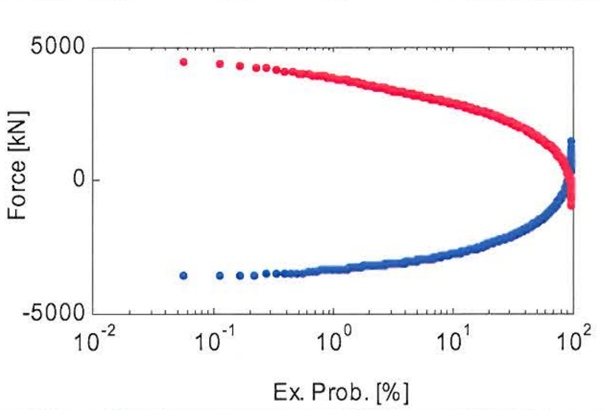
F13

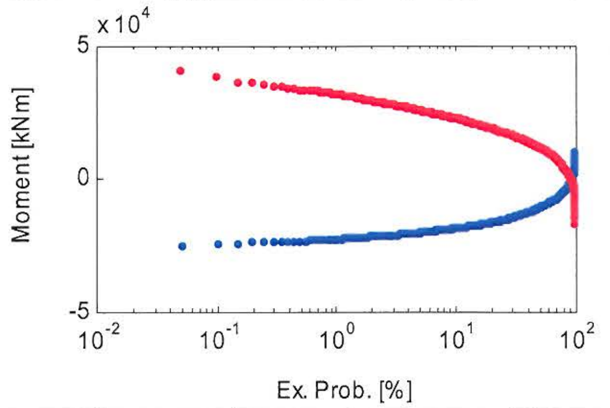
- With a concrete cone
- H_{m0} = 5.06 m, Tp = 9.1 s, h = 9 m
- $F_{h,max}$ = 5381 kN
- $F_{h,min}$ = -5251 kN
- M_{max} = 68899 kNm
- M_{min} = -77336 kNm

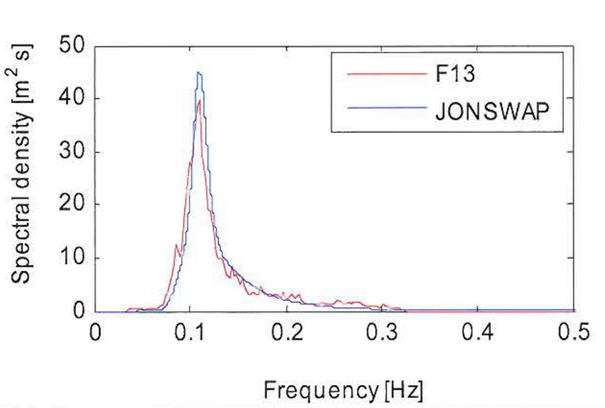


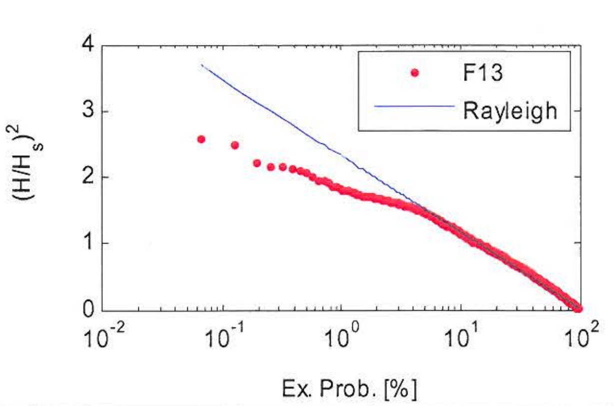






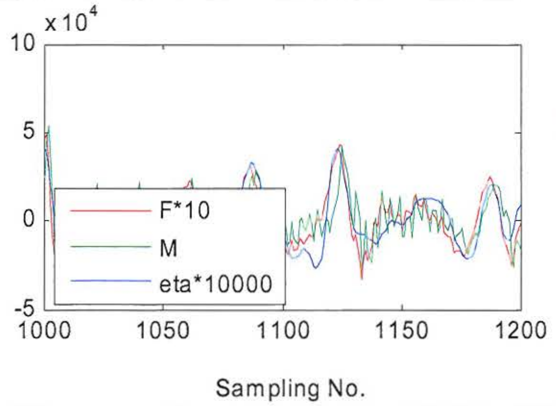


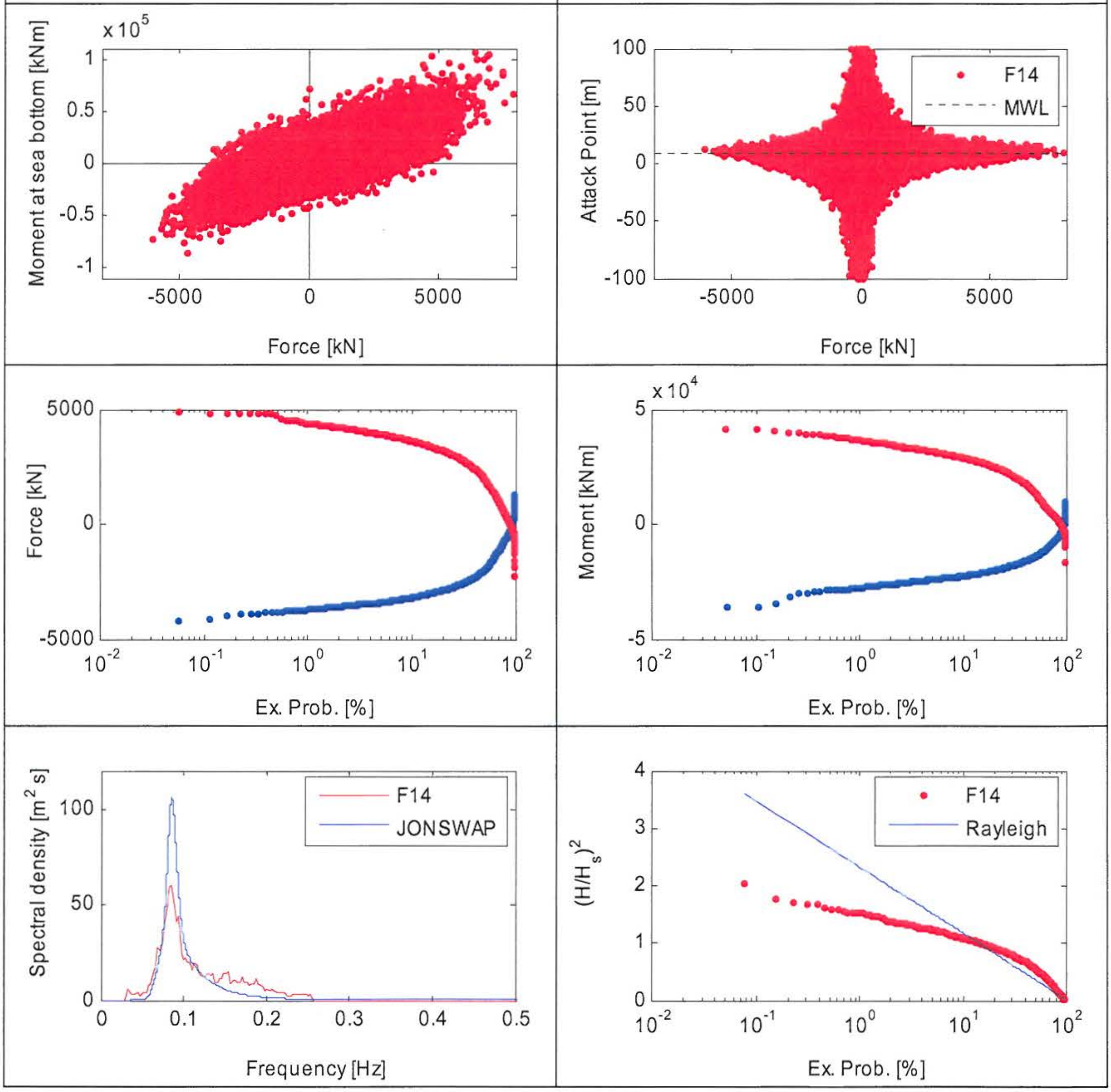




F14

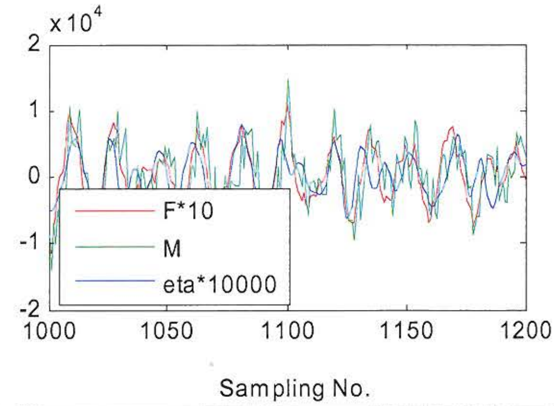
- With a concrete cone
- H_{m0} = 6.84 m, Tp = 11.7 s, h = 9 m
- $F_{h,max}$ = 7867 kN
- $F_{h,min}$ = -5986 kN
- M_{max} = 105442 kNm
- M_{min} = -85717 kNm

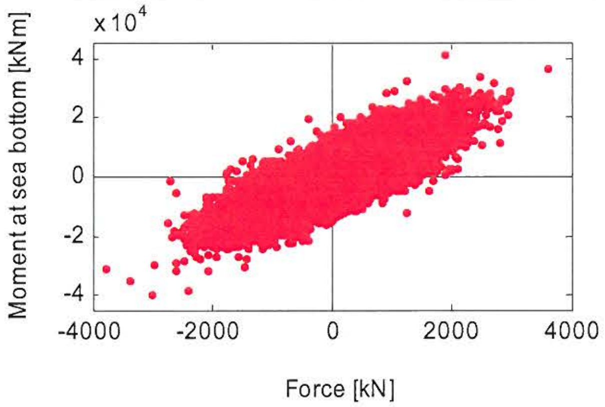


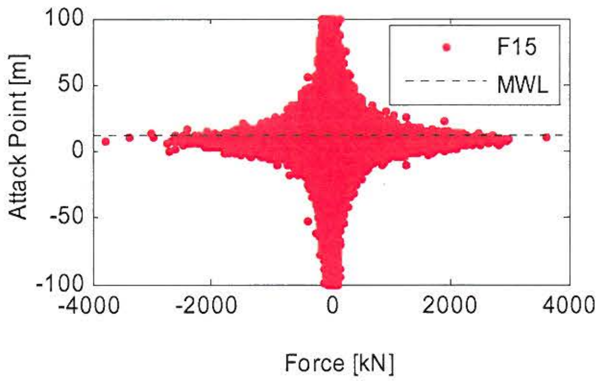


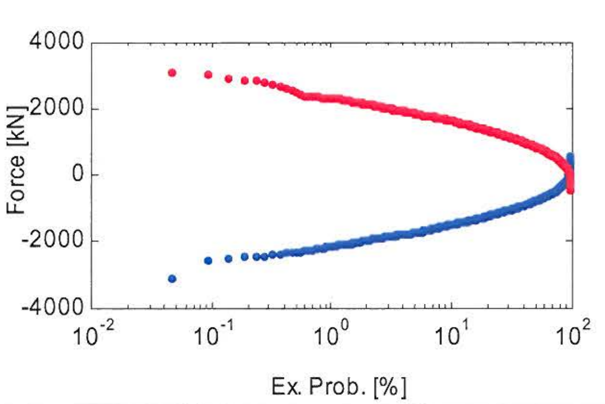
F15

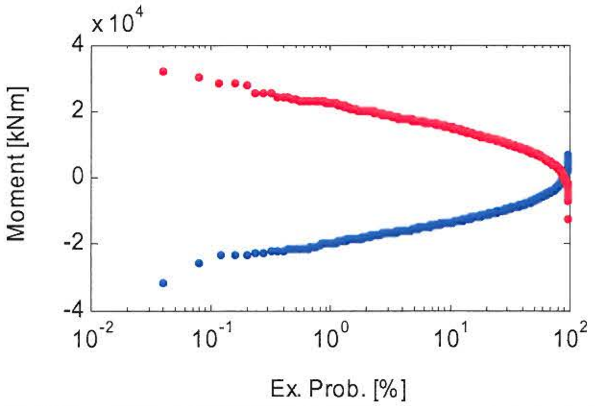
- With a concrete cone
- H_{m0} = 2.71 m, Tp = 6.5 s, h = 12 m
- $F_{h,max}$ = 3615 kN
- $F_{h,min}$ = -3781 kN
- M_{max} = 41461 kNm
- M_{min} = -40230 kNm

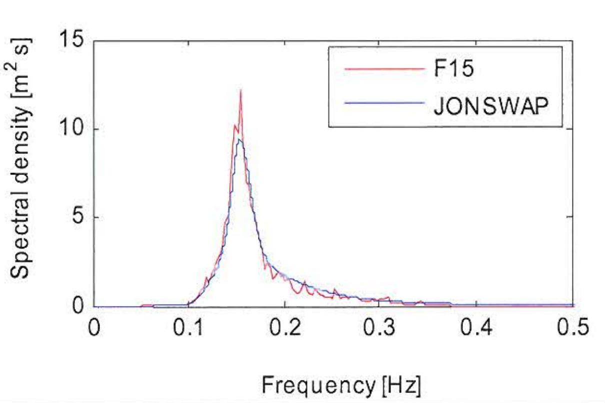


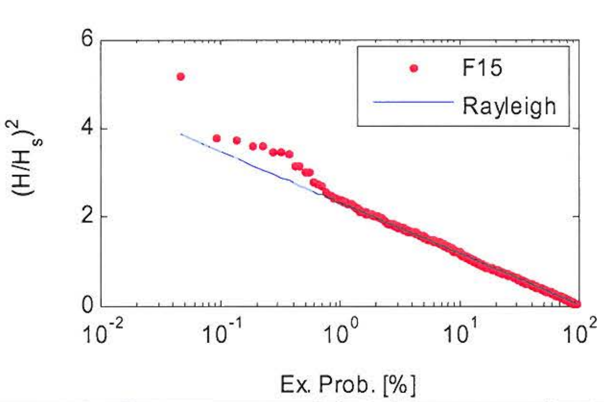






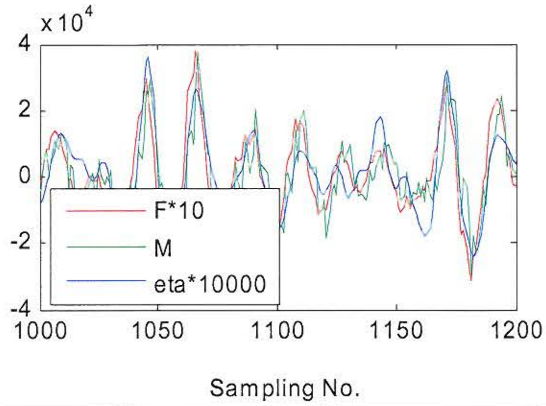


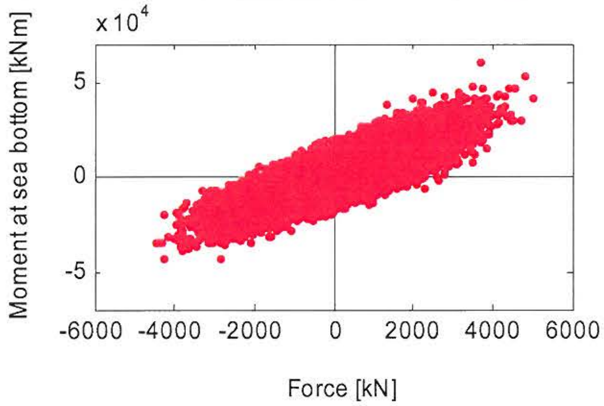


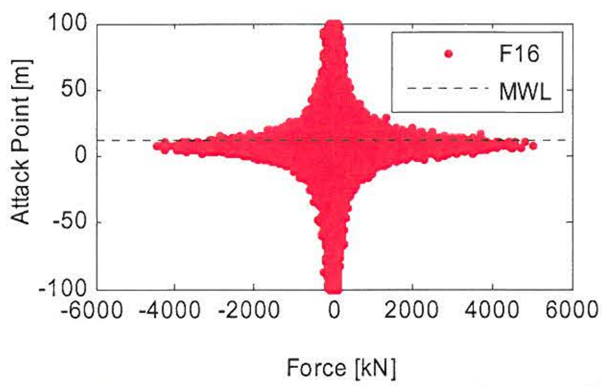


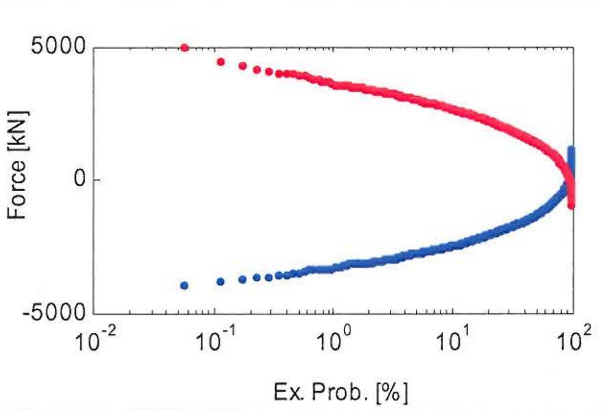
F16

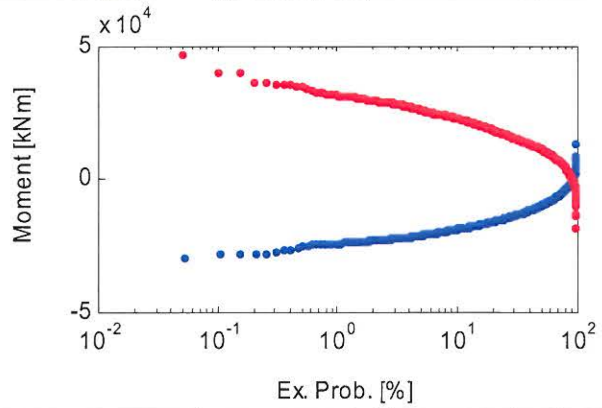
- With a concrete cone
- H_{m0} = 5.17 m, Tp = 9.1 s, h = 12 m
- $F_{h,max}$ = 5031 kN
- $F_{h,min}$ = -4476 kN
- M_{max} = 60476 kNm
- M_{min} = -43665 kNm

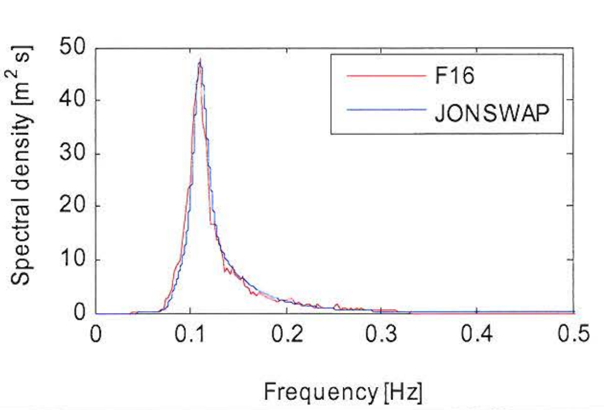


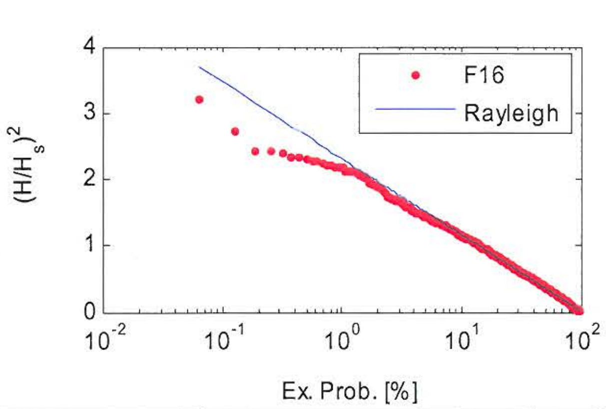






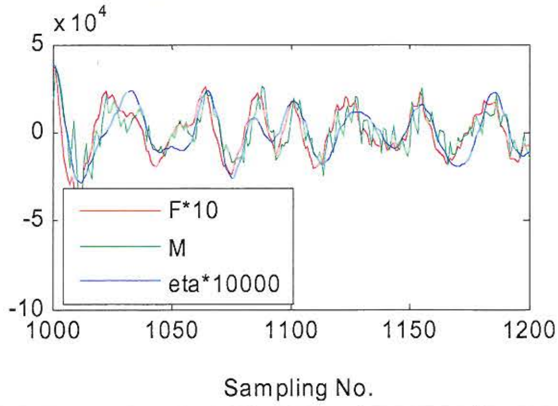


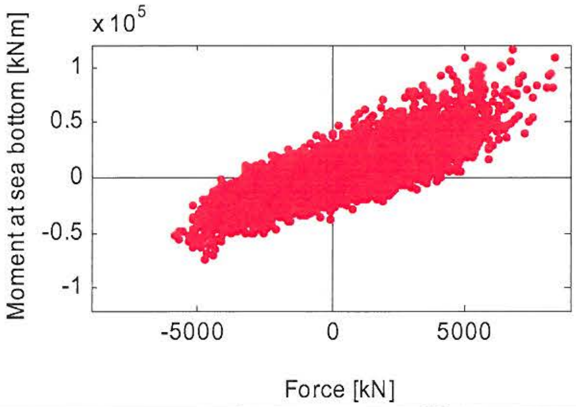


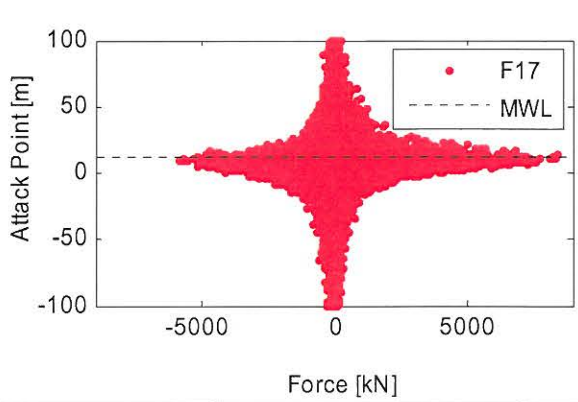


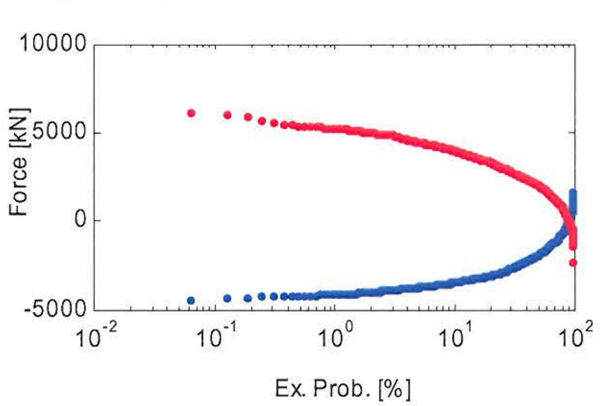
F17

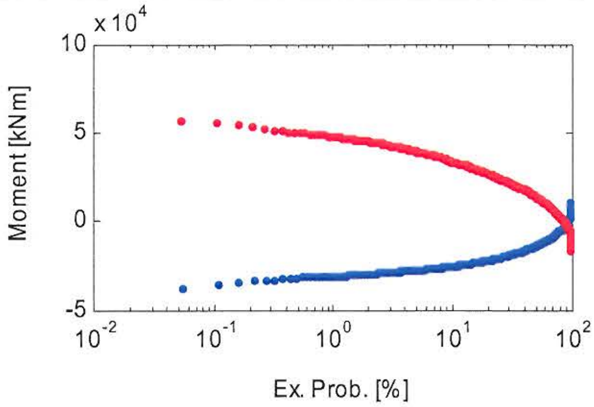
- With a concrete cone
- H_{m0} = 8.15 m, Tp = 11.7 s, h = 12 m
- $F_{h,max}$ = 8402 kN
- $F_{h,min}$ = -5833 kN
- M_{max} = 116356 kNm
- M_{min} = -74609 kNm

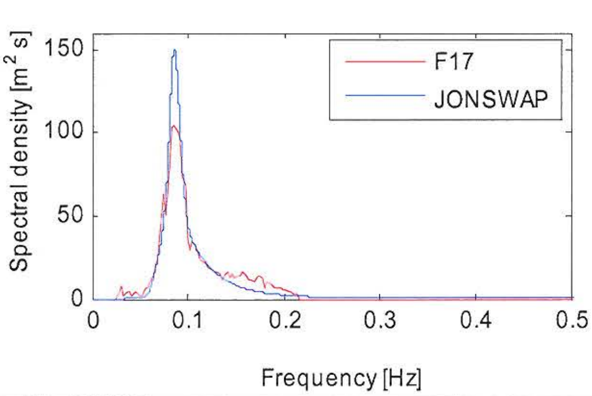


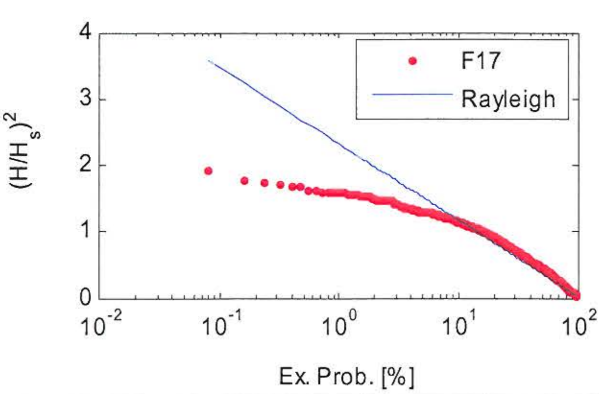






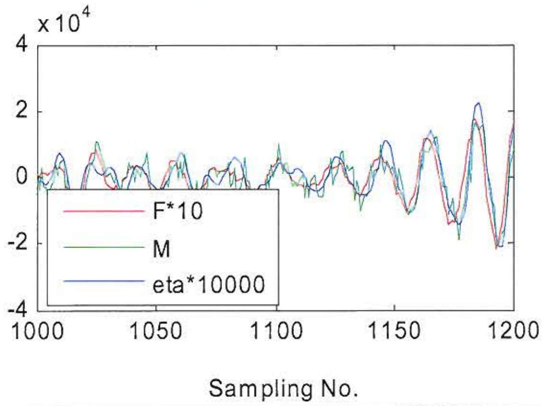


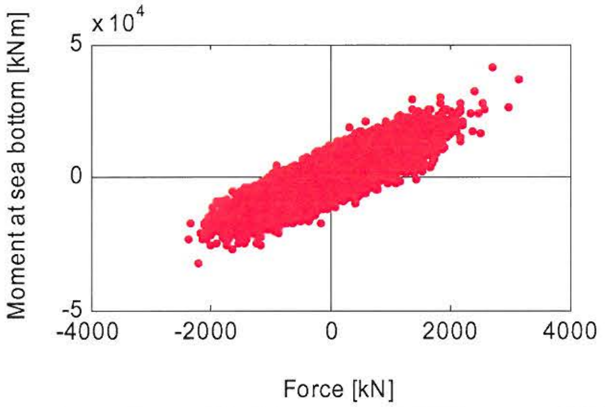


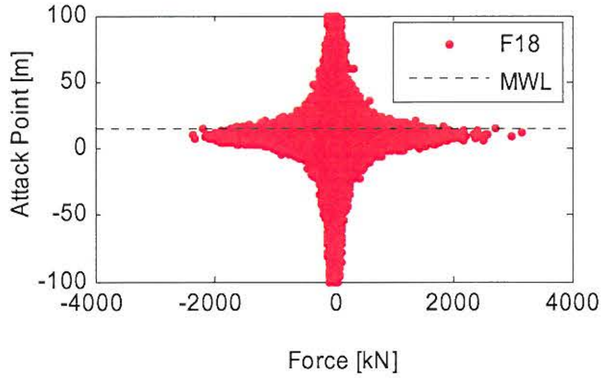


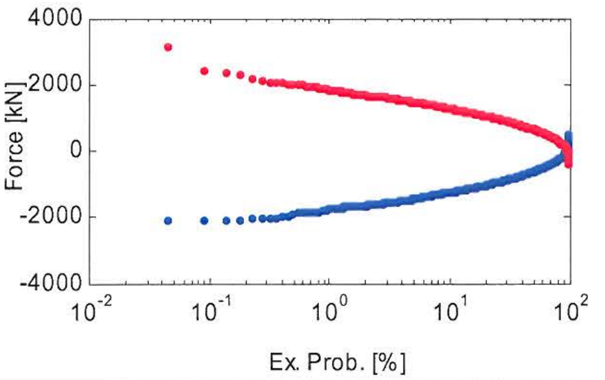
F18

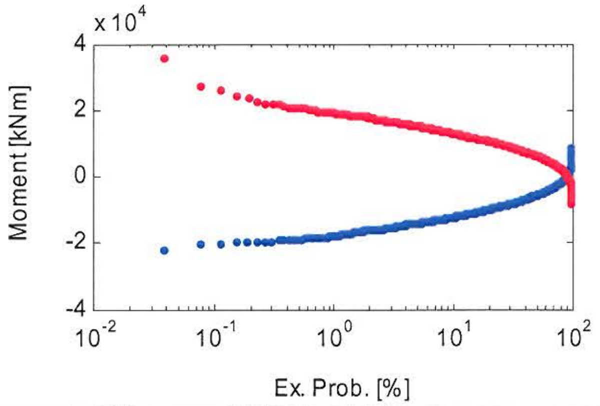
- With a concrete cone
- H_{m0} = 2.74 m, Tp = 6.5 s, h = 15 m
- $F_{h,max}$ = 3129 kN
- $F_{h,min}$ = -2373 kN
- M_{max} = 41116 kNm
- M_{min} = -32662 kNm

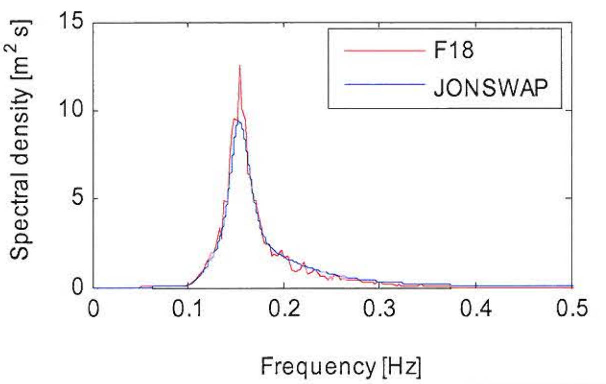


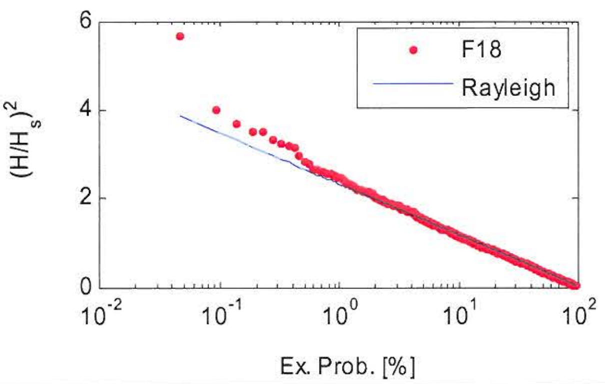






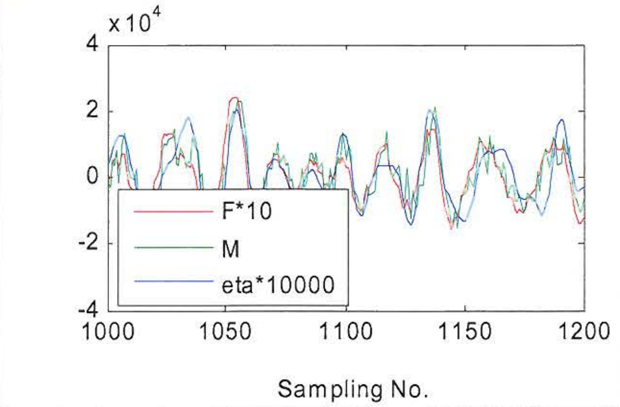


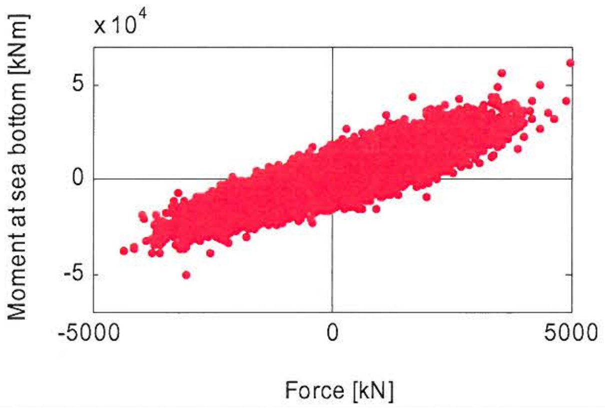


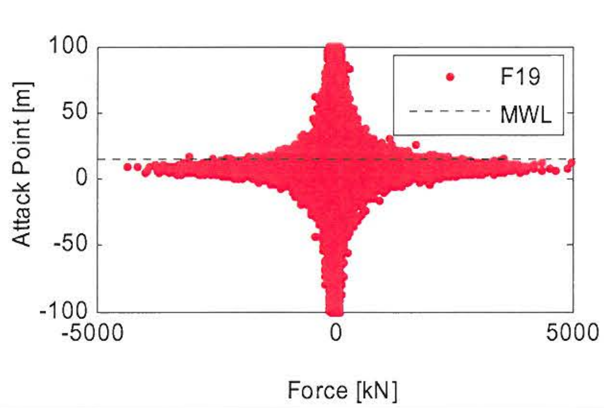


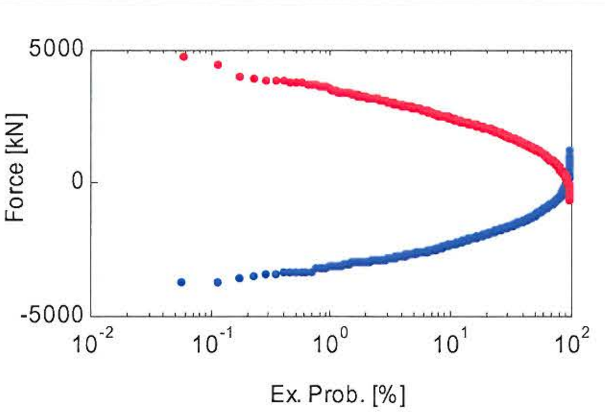
F19

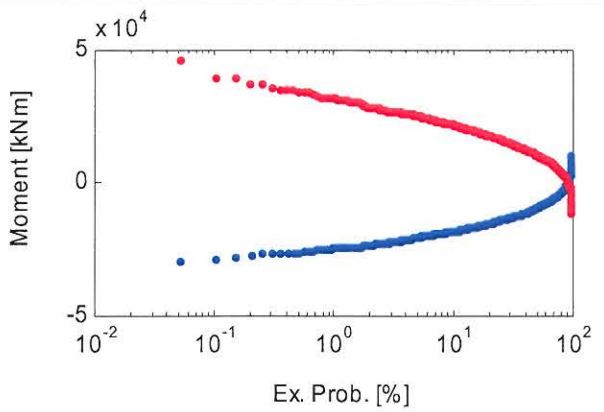
- With a concrete cone
- H_{m0} = 4.86 m, Tp = 9.3 s, h = 15 m
- $F_{h,max}$ = 4963 kN
- $F_{h,min}$ = -4337 kN
- M_{max} = 61444 kNm
- M_{min} = -50593 kNm

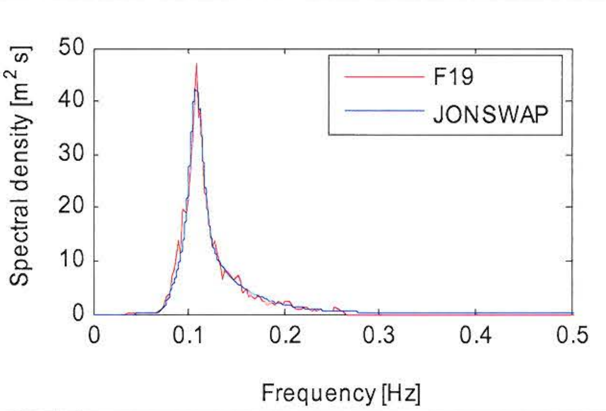


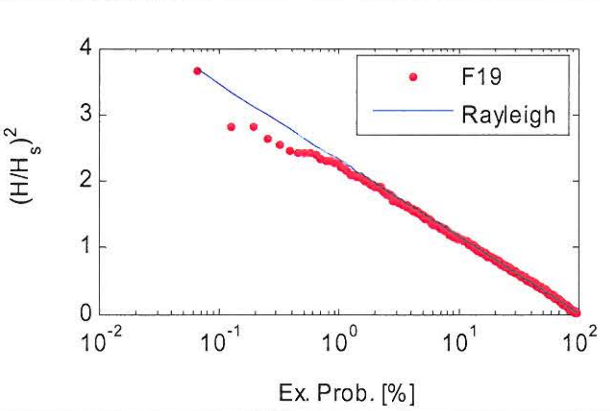






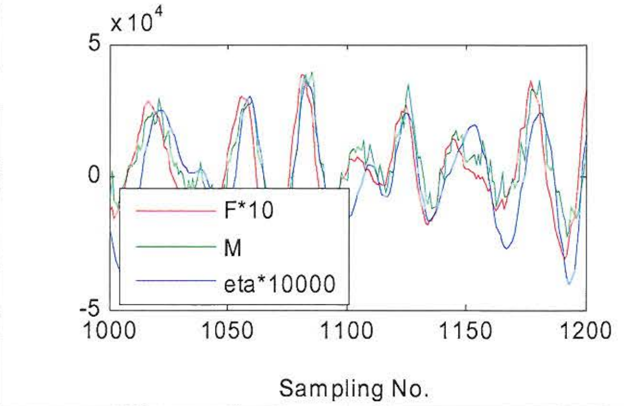


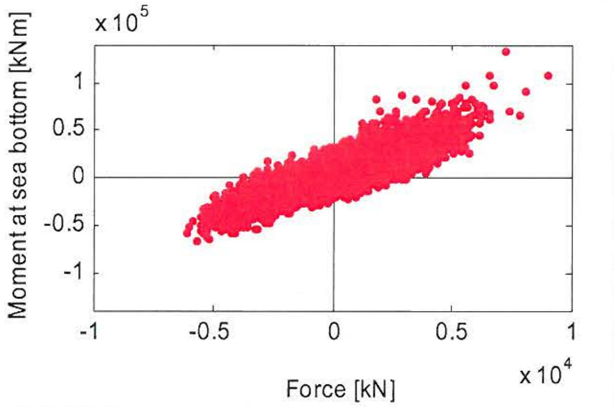


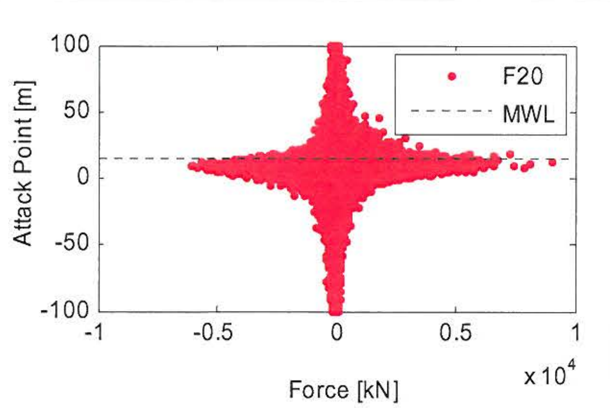


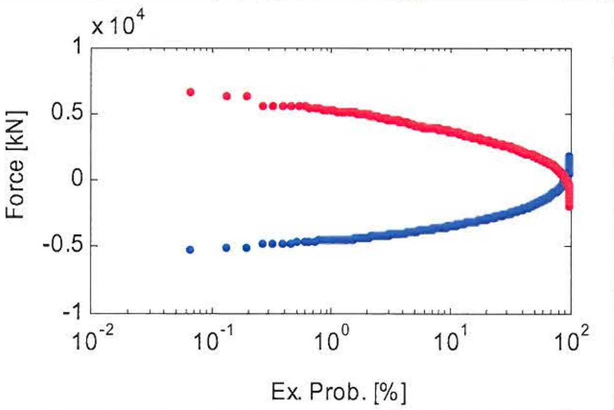
F20

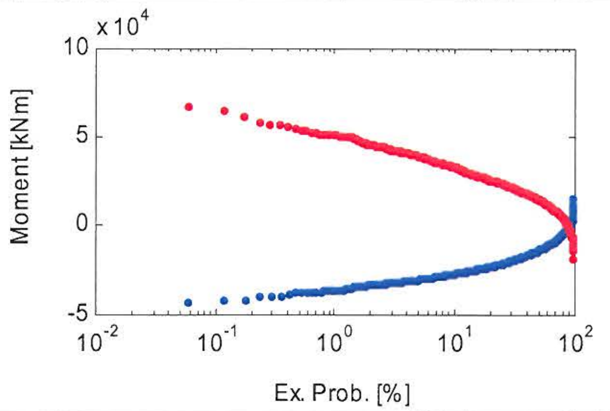
- With a concrete cone
- H_{m0} = 8.04 m, Tp = 11.3 s, h = 15 m
- $F_{h,max}$ = 9065 kN
- $F_{h,min}$ = -6098 kN
- M_{max} = 133309 kNm
- M_{min} = -68145 kNm

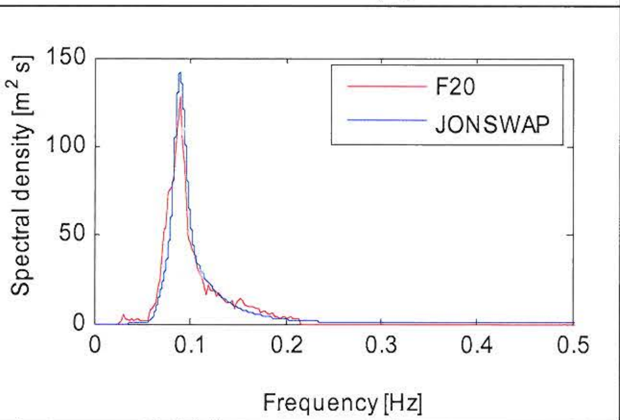


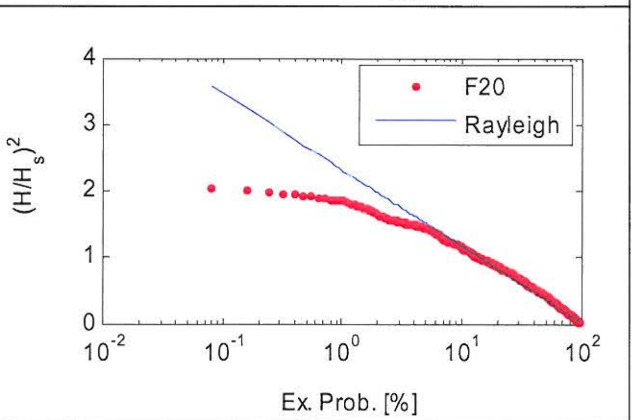






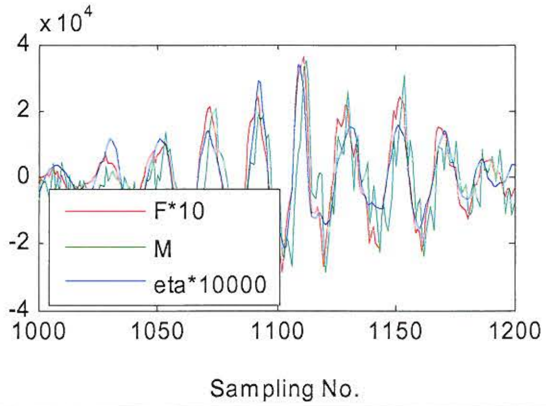


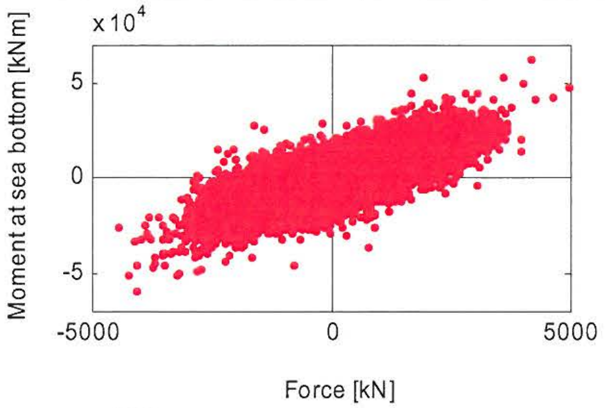


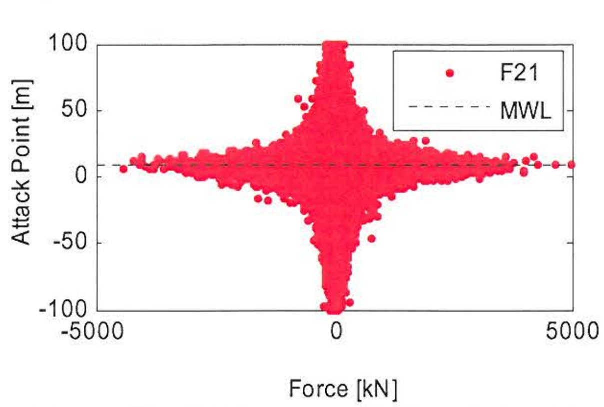


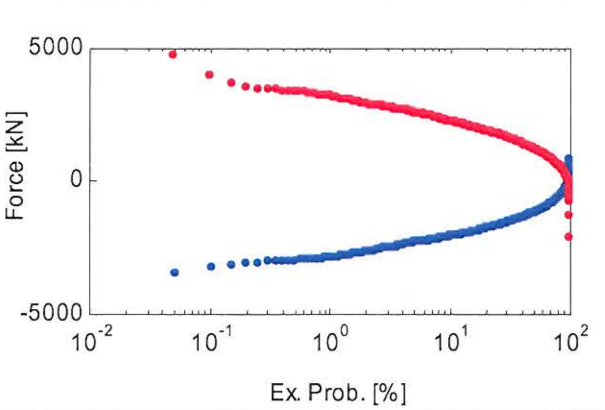
F21

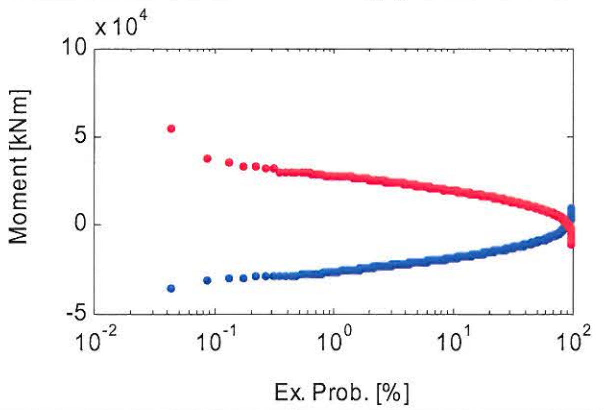
- With a concrete cone
- H_{m0} = 3.51 m, Tp = 6.5 s, h = 9 m, U = 1.5 m/s
- $F_{h,max}$ = 4991 kN
- $F_{h,min}$ = -4442 kN
- M_{max} = 62153 kNm
- M_{min} = -59566 kNm

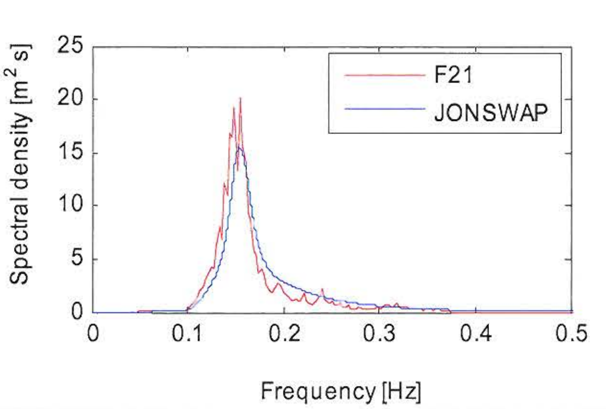


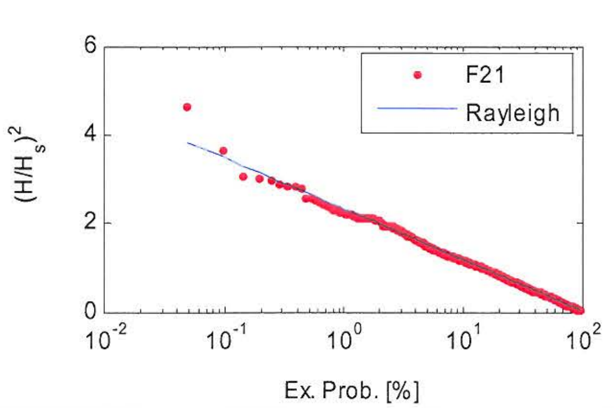






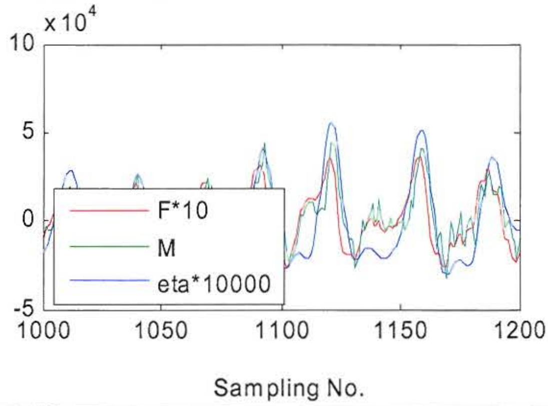


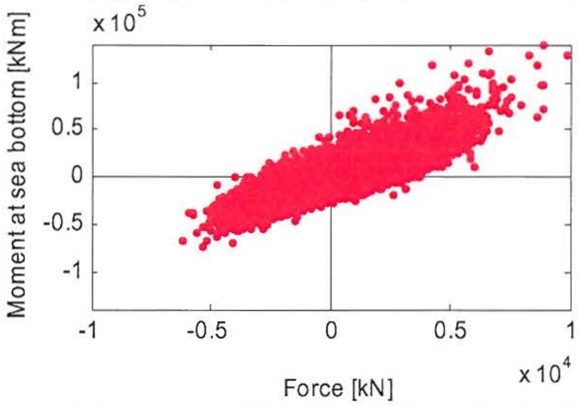


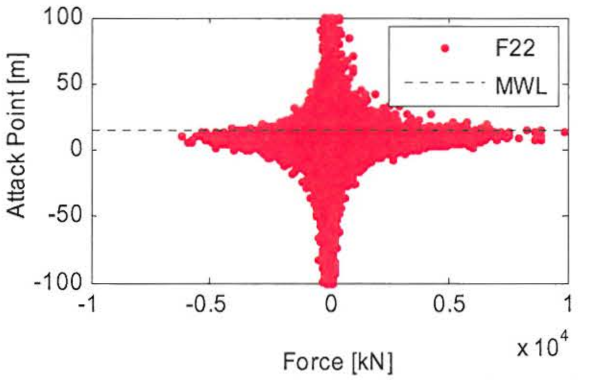


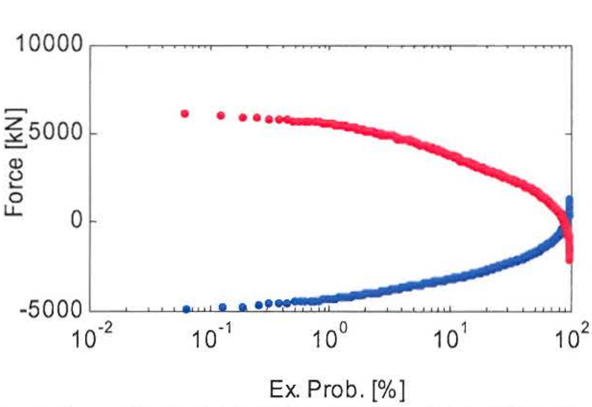
F22

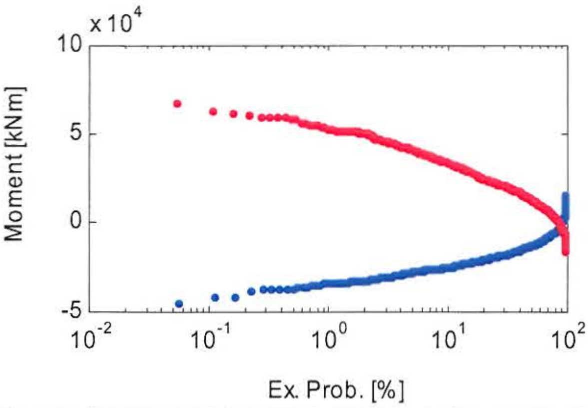
- With a concrete cone
- H_{m0} = 8.19 m, Tp = 11.3 s, h = 15 m, U = 1.5 m/s
- $F_{h,max}$ = 9894 kN
- $F_{h,min}$ = -6166 kN
- M_{max} = 139241 kNm
- M_{min} = -73882 kNm

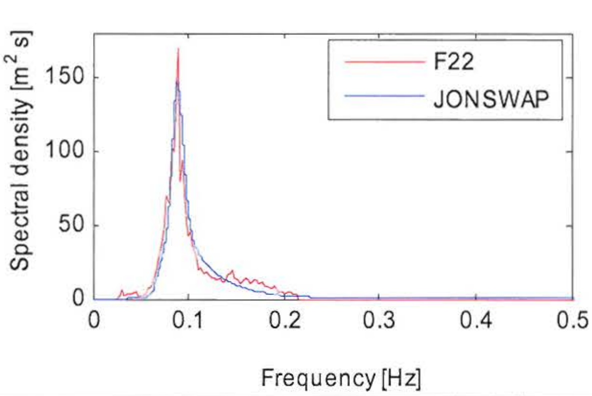


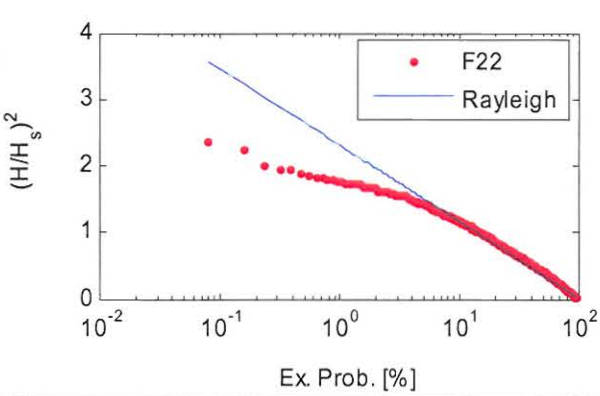






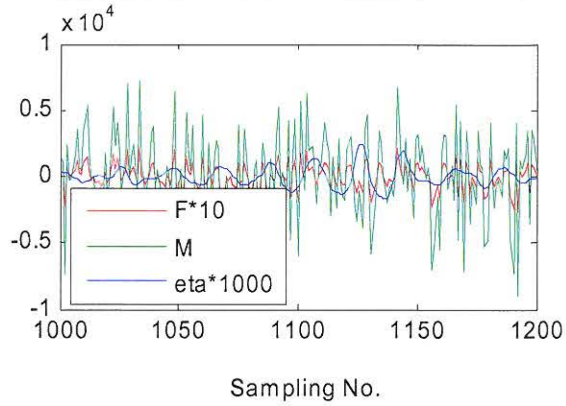


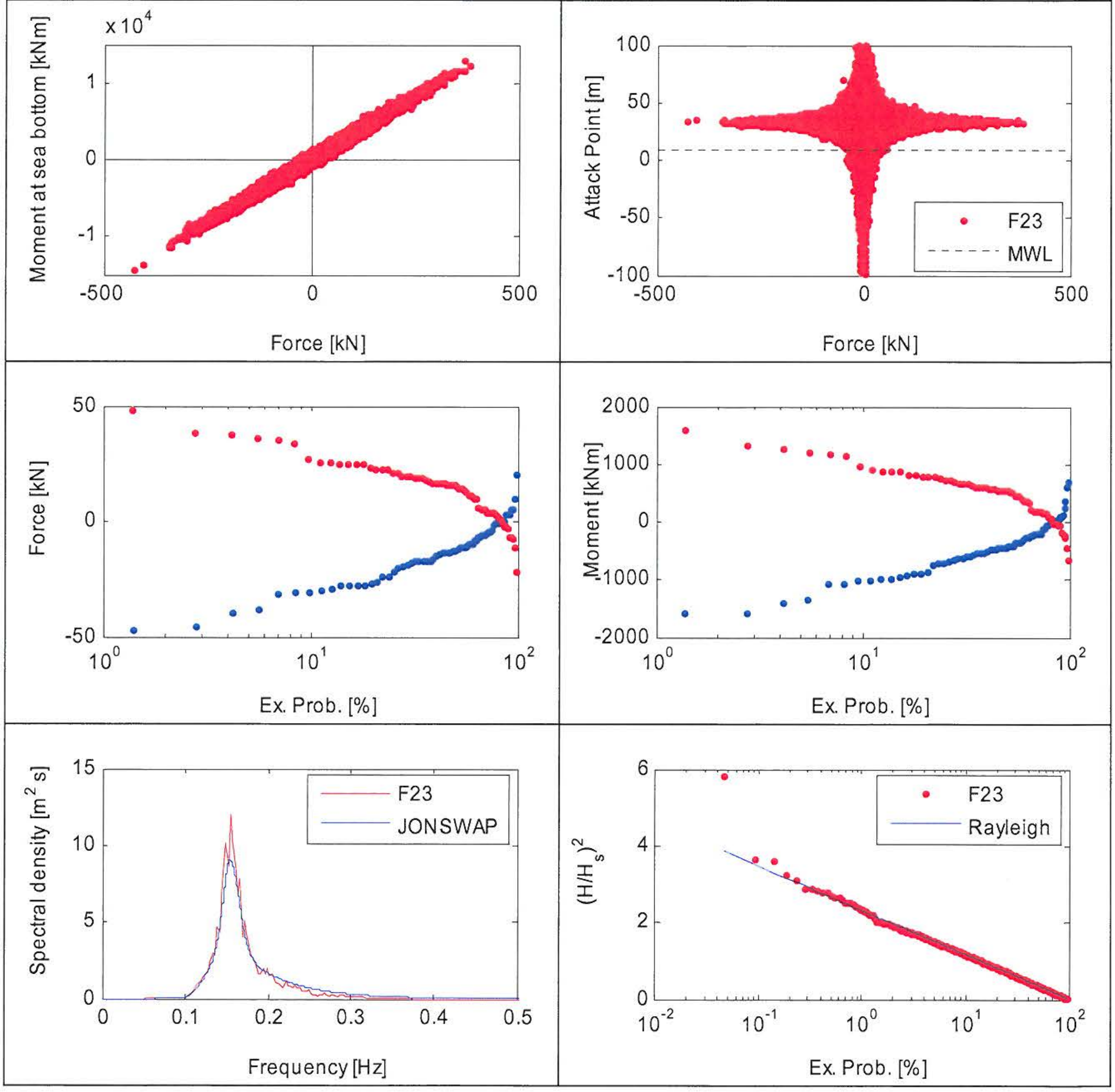




F23

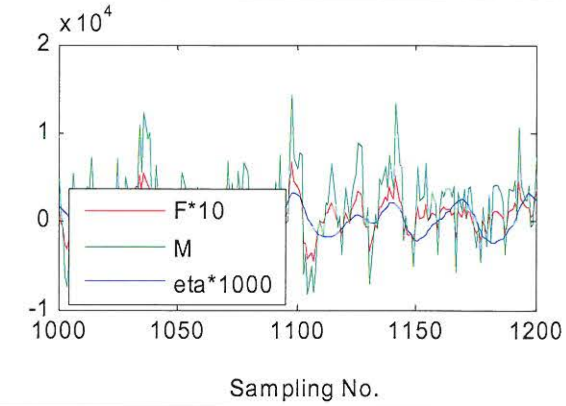
- With the shaft of the cone
- H_{m0} = 2.69 m, Tp = 6.5 s, h = 9 m
- $F_{h,max}$ = 384 kN
- $F_{h,min}$ = -428 kN
- M_{max} = 12900 kNm
- M_{min} = -14340 kNm

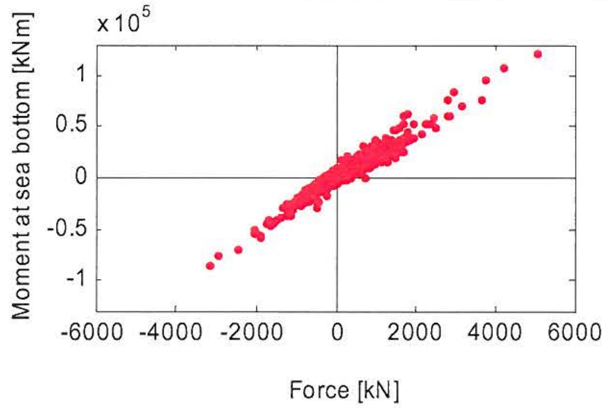


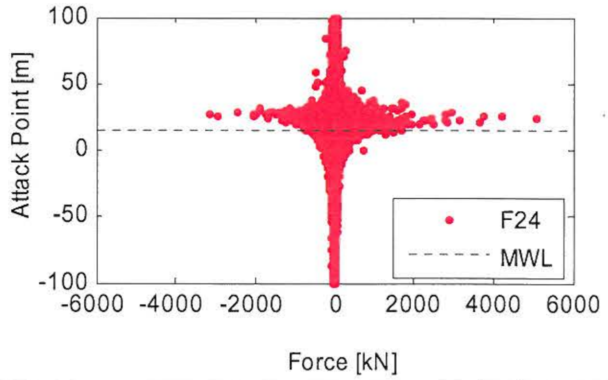


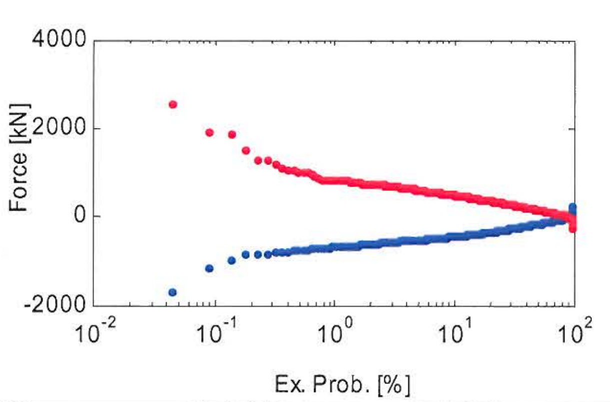
F24

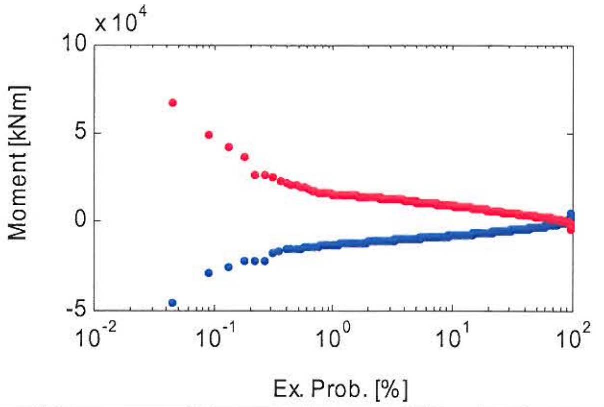
- With the shaft of the cone
- H_{m0} = 7.85 m, Tp = 11.3 s, h = 15 m
- $F_{h,max}$ = 5074 kN
- $F_{h,min}$ = -3152 kN
- M_{max} = 121939 kNm
- M_{min} = -85220 kNm

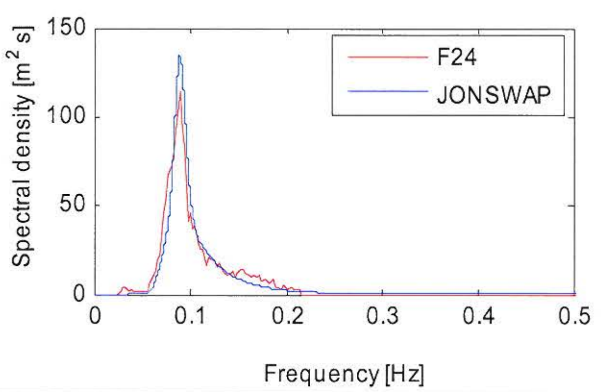


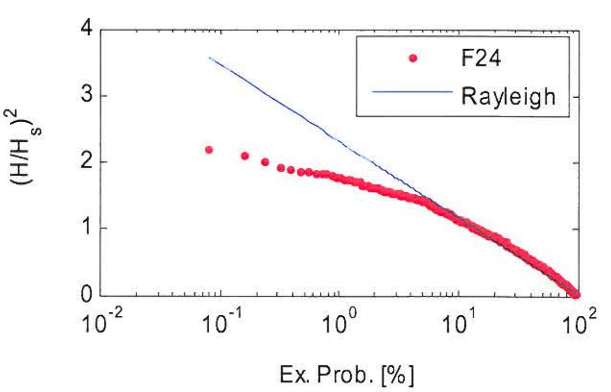








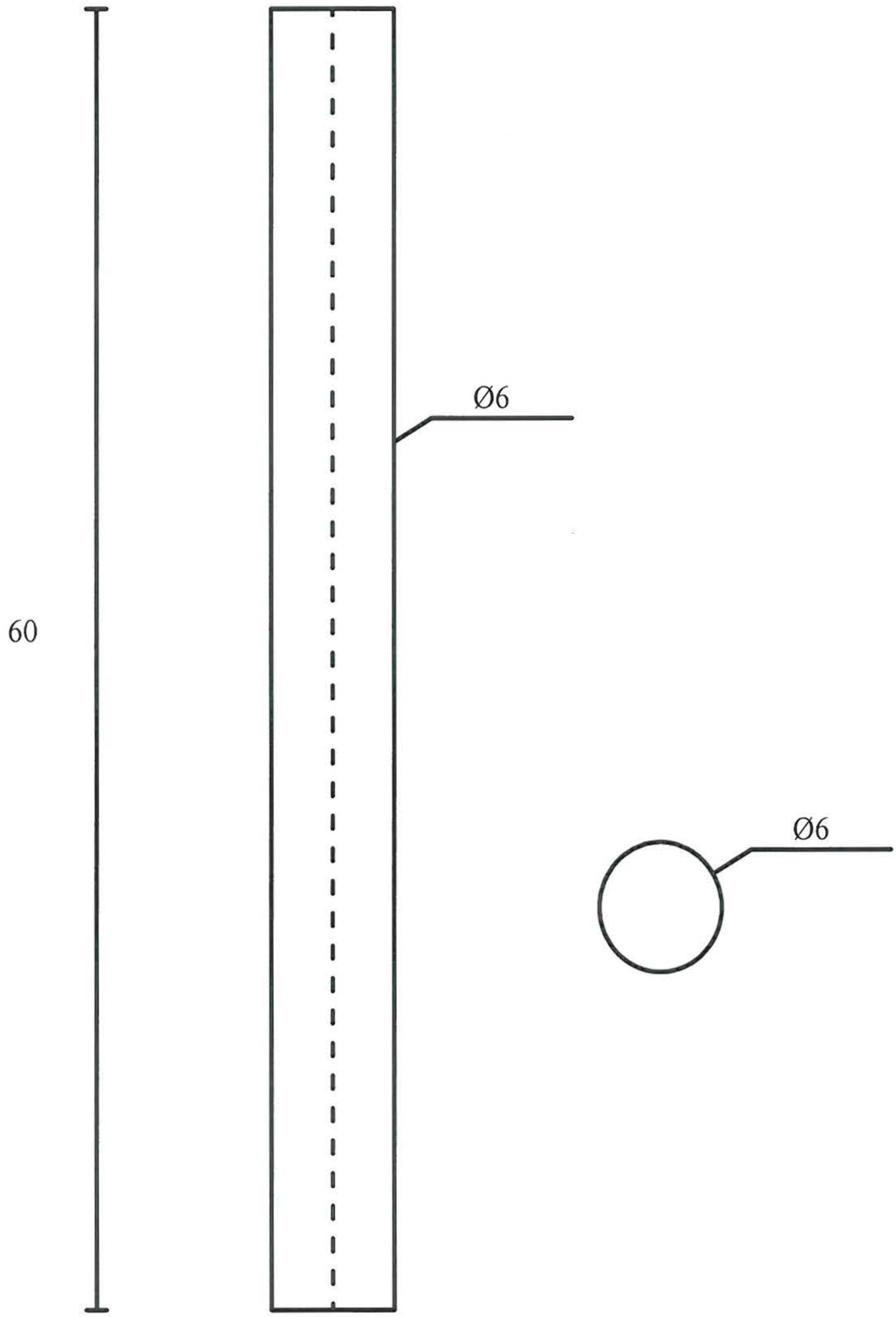




Appendix 2 - Models

All measures in meters – prototype values.

Monopile:



Concrete cone: